New Frontiers in the Solar System

An Integrated Exploration Strategy

Solar System Exploration Survey

Space Studies Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

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Support for this project was provided by Contracts NASW 96013 and 01001 between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsor.

International Standard Book Number 0-309-08495-4 (Book)
International Standard Book Number 0-309-50836-3 (PDF)

Cover design by Penny E. Margolskee

Copies of this report are available free of charge from:

Space Studies Board
National Research Council
The Keck Center of the National Academies
500 Fifth Street, N.W.
Washington, DC 20001

Printed in the United States of America

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Foreword

In 1957, on a dark hillside in Lincolnshire not far from the place where the young Isaac Newton grew up, I watched Sputnik travel inexorably across the twilight sky and was moved by the magnificence of it all. In the United States, the drama of the satellite's launch quickly led to the formation of the National Aeronautics and Space Administration (NASA) and the start of the exploration of the solar system. Forty-five years later, with millions of others, we have vicariously traveled to nearly every corner of the solar system and have learned how much more there is to discover and how imperfectly we understand the massive findings of past and current planetary missions and ground-based observations.

Exploration, discovery, and creative scientific research are the keys to new knowledge, and if we wish to know our origins and our destiny, whether we are unique or commonplace, and how nature governs our lives, we have no alternative but to explore the Sun's system of planets, satellites, comets, and asteroids to discover their secrets and understand the processes that make them what they are.

The exploration of the solar system is a technically challenging and expensive endeavor. Success is not always guaranteed, and tenacity and perseverance are required. Yet in the United States, as in some other countries, this challenge has been met with resolve. Today we are planning space missions that may tell us whether other life exists or has ever existed in places beyond Earth. We are engaged in research that probes from the very cores of planets to the atomic processes that occur in the highest regions of their atmospheres and plasma environments, and we are carrying out surveys to find potentially hazardous objects in near-Earth orbits that could affect the future of us all. Answers to some of the most profound questions—Are we alone? Where did we come from? What is our destiny?—may be within our grasp.

To continue this exploration in the most productive way, an effective strategy is needed that will produce the most significant results for the least time and resources spent. This is the purpose of the present survey, which was commissioned by NASA in 2001. It is to provide the scientific rationale for a ranked set of exploratory missions that could be launched in the coming decade. It must also integrate the wide range of interests—from atmospheric physics to geology and from cosmochemistry to astrobiology—of those engaged in this exploration. The survey is not an implementation plan; it is a durable strategy on which sound implementation plans can be securely based.

In February 2002, while the survey was in progress, a significant, if not pivotal, event occurred with the publication of the President's proposed budget for fiscal year 2003. The proposals in that budget for NASA's

Solar System Exploration program have excited planetary scientists for several reasons. These include the following:

- Strong support for continued Mars exploration and the line of small, competitively selected Discovery missions;
- Creation of a continuing line of competed, medium-class missions, to be called New Frontiers;
- Major new support for research and analysis programs; and
- Initiation of new in-space power and propulsion technology programs to lay the basis for advanced exploration missions in the more distant future.

As the reader will discover, this survey builds on the many positive aspects of the President's proposals.

This report is not intended to be read straight through. For those who seek a broad overview and a synopsis of the mission priorities and other recommendations, there is the Executive Summary. For ease of reading, the main text is presented in two parts that are self-contained and can be read separately.

Part One contains a broad survey of the subject, indicating what is known about the various classes of objects, current research directions and key scientific questions, and recommendations from the supporting panels to the Steering Group on appropriate mission strategies for the near future. Six survey panels, consisting of a total of about 50 leading scientists, contributed this extensive material, which is arranged in five chapters. These chapters should provide excellent reference material for readers who are interested in specific issues.

Part Two presents an integrated strategy for future exploration that was devised by the Steering Group using the material from the panels, together with direct inputs from the scientific community, NASA personnel, government and private laboratories, professional societies, and the interested public. This strategy is expressed in a short list of key scientific questions, a ranked list of conceptual missions that derive from these questions, and a series of recommendations for the decade 2003-2013. It is hoped that the reader will find the scope of this strategy as exciting and relevant as I do. The Steering Group anticipates that the cost of carrying it out is commensurate with the resources that are proposed in the President's 2003 budget. With unity of purpose, the mission plan that is presented in this document can be realized to the benefit of all.

Michael J.S. Belton, *Chair*
Tucson, Arizona
April 4, 2002

Preface

NASA's Office of Space Science (OSS) employs a relatively mature strategic planning process that relies heavily on input from the scientific community to establish the scientific basis and direction for its space- and ground-based research programs. The primary sources of this guidance are the independent scientific analyses and recommendations provided by reports of the National Academies, particularly those from the Space Studies Board (SSB). Using those independently developed science strategies as input, OSS then employs a roadmapping process that is carried out by NASA's internal committees, especially the Space Science Advisory Committee and its associated subcommittees.

This roadmapping process builds on the results of National Research Council (NRC) science strategies to define more detailed scientific objectives and investigations, as well as specific missions to address them. The roadmapping process factors in budget and technical aspects to refine the agency's portfolio of development options for the decade. The roadmaps constitute a major element of the triennial OSS strategic planning process, which in turn feeds into the overall NASA strategic plan that is revised every 3 years in compliance with the Government Performance and Results Act.

The last strategy for solar system exploration, the so-called Burns report,[a] was produced by the Space Studies Board in 1994. Since then, a number of important developments have led to the need for a new or substantially revised science strategy. These developments include significant changes in the way that NASA selects and manages its planetary exploration missions, with increasing emphasis on the "faster-better-cheaper" paradigm, and major new scientific results from a variety of spacecraft, including Lunar Prospector, Mars Pathfinder, Mars Global Surveyor, Galileo, Near Earth Asteroid Rendezvous, and Cassini. Moreover, since the publication of the Burns report, the SSB has produced more than a dozen relevant, focused, topical reports whose conclusions, integrated into a single, comprehensive strategy, would inform solar system exploration for the next decade.

Against this background, Edward J. Weiler, NASA's associate administrator for the Office of Space Science, requested that the SSB undertake a study designed to survey the current status of, and research strategies for, solar system exploration (see Appendix A). The study, outlined in letters sent to the SSB in January and April of 2001,

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[a]Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994.

was to be modeled on the traditional astronomy and astrophysics decadal surveys.[b] In particular, the report resulting from the requested study should include the following components:

- A "big picture" of solar system exploration—what it is, how it fits into other scientific endeavors, and why it is a compelling goal today;
- A broad survey of the current state of knowledge about our solar system today;
- An inventory of top-level scientific questions that should provide the focus for solar system exploration today; and
- A prioritized list of the most promising avenues for flight investigations and supporting ground-based activities.

NASA's request also contained several important caveats regarding the ongoing Mars exploration and Discovery programs and suggested that the time scale to be covered should be approximately a decade. Further clarification from NASA indicated that the ranked list of ground- and space-based initiatives should be subdivided into a small number of cost categories.

The NRC subsequently appointed the Solar System Exploration Survey (SSE Survey), consisting of a 15-member Steering Group and supporting panels, to perform the study. Because of the wide range of scientific disciplines and the varied nature of the targets of solar system exploration, four ad hoc panels were established to advise the steering group on issues involved in the exploration of particular targets. These panels concerned themselves with issues relating to the inner planets, the giant planets, large satellites, and primitive bodies. Moreover, given the relative timing of this study and another study for NASA on Mars science and mission priorities being undertaken by the NRC's Committee on Planetary and Lunar Exploration (COMPLEX), it was decided to recruit the latter as the SSE Survey's Mars Panel and to limit the Inner Planets Panel's deliberations to Mercury, Venus, and the Moon. To provide a clear communication path between the various components of the SSE Survey, the panel vice chairs were also appointed to the Steering Group.

Soon after the beginning of the SSE Survey's work, it became clear that special arrangements were needed to understand any issues involving astrobiology, which is already a substantial element of supporting research at NASA. Since an existing NRC group, the Committee on the Origins and Evolution of Life (COEL), already had the necessary expertise, it was decided to recruit COEL as the SSE Survey's Astrobiology Panel.

The four ad hoc and two preexisting panels were asked by the Steering Group to prepare a broad survey of the current state of knowledge of those elements of solar system exploration within their purview. In addition, they were asked to list the key scientific questions and measurement objectives that they deemed appropriate for exploration in the period 2003-2013 and the foreseeable future. The panels were also invited to bring to the Steering Group a ranked list of possible flight missions and supporting ground-based activities that were appropriate for addressing the measurement objectives they had identified. The reports of the panels, suitably edited for consistent presentation, are included in Part One (Chapters 1 through 5) of this report. The various lists of key scientific questions and ranked lists of flight missions and supporting ground-based facilities from the panels were considered by the Steering Group and were used to formulate the SSE Survey's top-level, integrated list of scientific questions and recommendations for priority flight missions and supporting ground-based facilities. These are contained in Chapters 7 and 8 of Part Two. Finally, an analysis of the solar system exploration program, its strengths and weaknesses, and why it is a compelling endeavor today—that is, the "big picture"—was undertaken by the Steering Group itself and is contained in Chapter 6 of Part Two.

Solar system exploration has a broad professional community with diverse scientific interests; it is also an international endeavor involving mission, research, and instrument activities in many countries. In view of this diversity, it quickly became clear to the Steering Group and its panels that to successfully reflect the interests of this community and to achieve a broad consensus of opinion in support of the SSE Survey's recommendations, it

[b]See, for example, Board on Physics and Astronomy and Space Studies Board, National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

would be necessary to stimulate and consider a wide variety of inputs from the scientific community, from NASA and its advisory committees, from other government agencies (principally the Office of Management and Budget and the National Science Foundation), from major laboratories and research institutes (particularly the Jet Propulsion Laboratory, Johns Hopkins University's Applied Physics Laboratory, and NASA's Astrobiology Institute), and from the interested public through the Planetary Society. That these inputs should be treated with exceptional care and appropriate seriousness was obvious and became the consistent policy of the SSE Survey. Such inputs were solicited through oral presentations to the Steering Group and its panels, through teleconferences, through numerous public forums and town hall sessions at major community meetings, and by stimulating, through the good offices of professional societies, a series of 24 community-drafted white papers (listed in Appendix B) on a wide range of scientific subjects that covered essentially all aspects of solar system exploration. Mark Sykes, then the chair of the Division for Planetary Sciences (DPS) of the American Astronomical Society, undertook the responsibility of coordinating the timely generation of these papers and worked with the DPS, the Planetary Sciences Section of the American Geophysical Union, the Meteoritical Society, and the Geological Society of America to accomplish this.

This project was formally initiated at a meeting of the Steering Group held in Washington, D.C., on July 19-20, 2001. Work continued at meetings held in Irvine, California (November 14-16), and Tucson, Arizona (February 26-March 1, 2002).

In parallel with these meetings, the SSE Survey's four ad hoc and two preexisting panels held their own information-gathering and deliberative meetings at NRC facilities and major centers for research in the planetary sciences (e.g., Boulder, Colorado; Tucson and Flagstaff, Arizona; Mountain View and Pasadena, California; and Providence, Rhode Island). The Steering Group and the panels made extensive use of teleconferences, e-mail, and a password-protected Web site to facilitate their work.

Final drafts of the panel reports were completed in February 2002. The Steering Group assembled the first full draft of this report in March and held its final meeting in Washington, D.C., on March 26-28, 2002. The text was sent to external and internal reviewers in late April, was revised during May and June, and was formally approved for release by the NRC on July 2, 2002. This report was publicly released in an unedited, prepublication format on July 9. This, the edited text of the report of the Solar System Exploration Survey, was prepared during the latter half of 2002 and finalized in February 2003. This version supersedes all other versions.

The work of the SSE Survey was made easier thanks to the important help given by numerous individuals at a variety of public and private organizations. These include, in no particular order, Mark Sykes, Steven Larson, and members of the Committee of the Division for Planetary Sciences (American Astronomical Society); James Head III (American Geophysical Union, Planetary Sciences Section); Gero Kurat and Ed Scott (Meteoritical Society); Ralph P. Harvey (Geological Society of America, Planetary Geology Division); Charles Elachi, Firouz Naderi, Daniel McCleese, Martha Hanner, and Douglas Stetson (Jet Propulsion Laboratory); John Appleby, Andrew Cheng, Stamatios Krimigis, and Ralph McNutt (Applied Physics Laboratory); Bruce Betts and Louis Friedman (Planetary Society); Marc Allen, James Garvin, Colleen Hartman, Orlando Figueroa, Michael Meyer, Carl Pilcher, Guenter Riegler, and Jeffrey Rosendhal (National Aeronautics and Space Administration); Vernon Pankonin (National Science Foundation); and Steven Isakowitz and Brant Sponberg (Office of Management and Budget).

In addition, the following individuals greatly assisted the work of the Steering Group: John Brandt (University of New Mexico), Michael Drake (University of Arizona), Harald Hiesinger (Brown University), Bruce Jakosky (University of Colorado), Tim McCoy (Smithsonian Institution), Michael Mendillo (Boston University), Robert Millis (Lowell Observatory), Allan Tokunaga (University of Hawaii), and Roger Yelle (University of Arizona). Finally, the SSE Survey acknowledges the important contributions made by persons too numerous to mention who contributed to the community white papers listed in Appendix B, who made presentations at the SSE Survey's numerous meetings and public forums, and who assisted the Survey's work in other ways.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We wish to thank the following individuals for their participation in the review of this report: James Arnold (University of California, San Diego), Raymond Arvidson (Washington University), Radford Byerly, Jr. (University of Colorado), Anita Cochran (University of Texas), Riccardo Giacconi (Associated Universities, Inc.), Bruce Jakosky (University of Colorado), Melissa McGrath (Space Telescope Science Institute), William McKinnon (Washington University), Juan Pérez-Mercader (Centro de Astrobiología, Madrid), Mark Richardson (California Institute of Technology), Frederic Taylor (Oxford University), Alar Toomre (Massachusetts Institute of Technology), and James Van Allen (University of Iowa).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Thomas M. Donahue (University of Michigan) and Richard Goody (Harvard University). Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Executive Summary

Solar system exploration is that grand human endeavor which reaches out through interplanetary space to discover the nature and origins of the system of planets in which we live and to learn whether life exists beyond Earth. It is an international enterprise involving scientists, engineers, managers, politicians, and others, sometimes working together and sometimes in competition, to open new frontiers of knowledge. It has a proud past, a productive present, and an auspicious future.

Solar system exploration is a compelling activity. It places within our grasp answers to basic questions of profound human interest: Are we alone? Where did we come from? What is our destiny? Further, it leads to the creation of knowledge that will improve the human condition. Mars and icy satellite explorations may soon provide an answer to the first of these questions. Exploration of comets, primitive asteroids, and Kuiper Belt objects may have much to say about the second. Surveys of near-Earth objects and further exploration of planetary atmospheres will show something about the third. Finally, explorations of all planetary environments will result in a much improved understanding of the natural processes that shape the world in which we live.

This survey was requested by the National Aeronautics and Space Administration (NASA) to determine the contemporary nature of solar system exploration and why it remains a compelling activity today. A broad survey of the state of knowledge was requested. In addition, NASA asked for identification of the top-level scientific questions to guide its ongoing program and a prioritized list of the most promising avenues for flight investigations and supporting ground-based activities. To accomplish this task, the Solar System Exploration Survey's (SSE Survey's) Steering Group and panels have worked with scientists, professional societies, NASA and National Science Foundation (NSF) officials, people at government and private laboratories, and members of the interested public. The remarkable breadth and diversity in the subject are evident in the panel reports that constitute Part One of this survey. Together they strongly reinforce the idea that a high-level integration of the goals, ideas, and requirements that exist in the community is essential if a practical exploration strategy for the next decade is to emerge. Such an integrated strategy is the objective of Part Two.

CROSSCUTTING THEMES AND KEY QUESTIONS

Based on the material presented in Part One of this report, the SSE Survey identified the following four crosscutting themes that form an appropriate basis for an integrated strategy that can be realized by a series of missions to be flown over the next decade:

1. *The First Billion Years of Solar System History.* This first theme covers the formative period that features the initial accretion and development of Earth and its sibling planets, including the emergence of life on our globe. This pivotal epoch in the solar system's history is only dimly glimpsed at present.

2. *Volatiles and Organics: The Stuff of Life.* The second theme addresses the reality that life requires organic materials and volatiles, notably, liquid water. These materials originally condensed in the outer reaches of the solar nebula and were later delivered to the planets aboard organic-rich comets and asteroids.

3. *The Origin and Evolution of Habitable Worlds.* The third theme recognizes that our concept of the "habitable zone" has been overturned, and greatly broadened, by recent findings on Earth and elsewhere throughout our galaxy. Taking inventory of our planetary neighborhood will help to trace the evolutionary paths of the other planets and the eventual fate of our own.

4. *Processes: How Planetary Systems Work.* The fourth theme seeks deeper understanding of the fundamental mechanisms operating in the solar system today. Comprehending such processes—and how they apply to planetary bodies—is the keystone of planetary science. It will provide deep insight into the evolution of all the worlds within the solar system and of the multitude of planets being discovered around other stars.

Devolving from these four crosscutting themes are 12 key scientific questions. These are shown in Table ES.1, together with the names of the facilities and missions recommended as the most appropriate activities to address these questions. The priority and measurement objectives of these various projects are summarized in the next section.

PRIORITIES FOR FLIGHT MISSIONS AND ADVANCED TECHNOLOGY

Progress on the tabulated scientific themes and key questions will require a series of spaceflights and supporting Earth-based activities. It is crucial to maintain a mix of mission sizes and complexities in order to balance available resources against potential schemes for implementation. For example, certain aspects of the key science questions can be met through focused and cost-effective Discovery missions (<$325 million), while other high-priority science issues will require larger, more capable projects, to be called New Frontiers. About once per decade, Flagship missions (>$650 million) will be necessary for sample return or comprehensive investigations of particularly worthy targets. Some future endeavors are so vast in scope or so difficult (e.g., sample return from Mars) that no single nation acting alone may be willing to allocate all of the resources necessary to accomplish them, and **the SSE Survey recommends that NASA encourage and continue to pursue cooperative programs with other nations**. Not only is the investigation of our celestial neighborhood inherently an international venture, but the U.S. Solar System Exploration program will also benefit programmatically and scientifically from such joint ventures.

Discovery missions are reserved for innovative and competitively procured projects responsive to new findings beyond the nation's long-term strategy. Such missions can satisfy many of the objectives identified in Part One by the individual panels. **Given Discovery's highly successful start, the SSE Survey endorses the continuation of this program, which relies on principal-investigator leadership and competition to obtain the greatest science return within a cost cap. A flight rate of no less than one launch every 18 months is recommended.**

Particularly critical in this strategy is the initiation of New Frontiers, a line of medium-class, principal-investigator-led missions as proposed in the President's fiscal year (FY) 2003 budget. **The SSE Survey strongly endorses the New Frontiers initiative. These spacecraft should be competitively procured and should have flights every 2 or 3 years, with the total cost capped at approximately twice that of a Discovery mission. Target selection should be guided by the list in this report.**

Experience has shown that large missions, which enable detailed, extended, and scientifically multifaceted observations, are an essential element of the mission mix. They allow the comprehensive exploration of science targets of extraordinarily high interest. Comparable past missions have included Viking, Voyager, Galileo, and Cassini-Huygens. **The SSE Survey recommends that Flagship (>$650 million) missions be developed and flown at a rate of about one per decade. In addition, for large missions of such inclusive scientific breadth, a broad cross section of the community should be involved in the early planning stages.**

TABLE ES.1 Crosscutting Themes, Key Scientific Questions, Missions, and Facilities

Crosscutting Themes and Key Questions	Recommended New Missions and Facilities
The First Billion Years of Solar System History	
1. What processes marked the initial stages of planet and satellite formation?	Comet Surface Sample Return Kuiper Belt-Pluto Explorer South Pole-Aitken Basin Sample Return
2. How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas giant sibling, Saturn?	Jupiter Polar Orbiter with Probes
3. How did the impactor flux decay during the solar system's youth, and in what way(s) did this decline influence the timing of life's emergence on Earth?	Kuiper Belt-Pluto Explorer South Pole-Aitken Basin Sample Return
Volatiles and Organics: The Stuff of Life	
4. What is the history of volatile compounds, especially water, across the solar system?	Comet Surface Sample Return Jupiter Polar Orbiter with Probes Kuiper Belt-Pluto Explorer
5. What is the nature of organic material in the solar system and how has this matter evolved?	Comet Surface Sample Return Cassini Extended
6. What global mechanisms affect the evolution of volatiles on planetary bodies?	Venus In Situ Explorer Mars Upper Atmosphere Orbiter
The Origin and Evolution of Habitable Worlds	
7. What planetary processes are responsible for generating and sustaining habitable worlds, and where are the habitable zones in the solar system?	Europa Geophysical Explorer Mars Science Laboratory Mars Sample Return
8. Does (or did) life exist beyond Earth?	Mars Sample Return
9. Why have the terrestrial planets differed so dramatically in their evolutions?	Venus In Situ Explorer Mars Science Laboratory Mars Long-Lived Lander Network Mars Sample Return
10. What hazards do solar system objects present to Earth's biosphere?	Large Synoptic Survey Telescope
Processes: How Planetary Systems Work	
11. How do the processes that shape the contemporary character of planetary bodies operate and interact?	Kuiper Belt-Pluto Explorer South Pole-Aitken Basin Sample Return Cassini Extended Jupiter Polar Orbiter with Probes Venus In Situ Explorer Comet Surface Sample Return Europa Geophysical Explorer Mars Science Laboratory Mars Upper Atmosphere Orbiter Mars Long-Lived Lander Network Mars Sample Return
12. What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?	Jupiter Polar Orbiter with Probes Cassini Extended Kuiper Belt-Pluto Explorer Large Synoptic Survey Telescope

NOTE: Since missions in the Discovery and Mars Scout lines might address many of these scientific topics, they are not shown, in order to maintain clarity.

Programmatic efficiencies are often gained by extending operational flights beyond their nominal lifetimes. Current candidates for continuation include Cassini, projects in the Mars Exploration Program, and several Discovery flights. **The SSE Survey supports NASA's current Senior Review process for deciding the scientific merits of a proposed mission extension and recommends that early planning be done to provide adequate funding of mission extensions, particularly Flagship missions and missions with international partners.**

Because resources are finite, the SSE Survey prioritized all new flight missions within each category along with any associated activities. To assess priorities in the selection of particular missions, it used the following criteria: scientific merit, "opportunity," and technological readiness. Scientific merit was measured by judging whether a project has the possibility of creating or changing a paradigm and whether the new knowledge that it produces will have a pivotal effect on the direction of future research, and, finally, on the SSE Survey's appraisal of how that knowledge would substantially strengthen the factual base of current understanding.

Because of wide differences in mission scope and the diverse circumstances of implementation, the SSE Survey, at NASA's request, prioritized only within three cost classes: small (<$325 million), medium ($325 million to $650 million), and large (>$650 million). Also, since the Mars Exploration Program line is already successfully established as a separate entity within NASA, its missions are prioritized separately in this report.

The recommendations from the SSE Survey's panels have been integrated with the Solar System Exploration program's overall goals and key questions in order to arrive at the flight-mission priorities listed in Table ES.2. The SSE Survey has included five New Frontiers missions in its priority list, recognizing that not all might be affordable within the constraints of the budgets available over the next decade.

Recommended Solar System Flight Missions (non-Mars)

Europa Geophysical Explorer

The Europa Geophysical Explorer (EGE), a Flagship mission, will investigate the probable subsurface ocean of Europa and its overlying ice shell as the critical first step in understanding the potential habitability of icy satellites. While orbiting Europa, EGE will employ gravity and altimetry measurements of Europa's tidal fluctuations to define the properties of any interior ocean and characterize the satellite's ice shell. Additional remote-sensing observations will examine the three-dimensional distribution of subsurface liquid water; elucidate the formation of surface features, including sites of current or recent activity; and identify and map surface composition, with emphasis on compounds of astrobiological interest. Prior to Europa-orbit insertion, EGE's instruments will scrutinize Ganymede and Callisto, moons that also may have subsurface oceans, thereby illuminating Europa's planetary and astrobiological context. Europa's thorough reconnaissance is a stepping stone toward understanding the astrobiological potential of all icy satellites and will pave the way for future landings on this intriguing object.

Kuiper Belt-Pluto Explorer

The Kuiper Belt-Pluto Explorer (KBP) will be the first spacecraft dispatched for scientific measurements within this remote, entirely unexplored outer half of the solar system. KBP will fly past Pluto-Charon and continue on to do reconnaissance of several additional Kuiper Belt objects (KBOs). KBP's value increases as it observes more KBOs and investigates the diversity of their properties. This region should be home for the most primitive material in the solar system. KBP will address the prospect that KBOs have played a role in importing basic volatiles and molecular stock to the inner solar system, where habitable environments were created. The SSE Survey anticipates that the information returned from this mission might lead to a new paradigm for the origin and evolution of these objects and their significance in the evolution of objects in other parts of the solar system.

South Pole-Aitken Basin Sample Return

The South Pole-Aitken Basin Sample Return (SPA-SR) mission will return samples from the Moon in order to constrain the early impact history of the inner solar system and to comprehend the nature of the Moon's upper

TABLE ES.2 Prioritized List of New Flight Missions for the Decade 2003-2013

Priority in Cost Class	Mission Concept Name	Description
SOLAR SYSTEM FLIGHT MISSIONS (non-Mars)		
Small (< $325 million)		
1	Discovery missions at one launch every 18 months	Small, innovative, principal-investigator-led exploration missions
2	Cassini Extended	Orbiter mission at Saturn
Medium (< $650 million)		
1	Kuiper Belt-Pluto Explorer	A flyby mission of several Kuiper Belt objects, including Pluto/Charon, to discover their physical nature and understand their endowment of volatiles
2	South Pole-Aitken Basin Sample Return	A mission to return samples from the solar system's deepest crater, which pierces the lunar mantle
3	Jupiter Polar Orbiter with Probes	A close-orbiting polar spacecraft equipped with various instruments and a relay for three probes that make measurements below the 100+ bar level
4	Venus In Situ Explorer	A core sample of Venus to be lifted into the atmosphere for compositional analysis; simultaneous atmospheric measurements
5	Comet Surface Sample Return	Several pieces of a comet's surface to be returned to Earth for organic analysis
Large (>$650 million)		
1	Europa Geophysical Explorer	An orbiter of Jupiter's ice-encrusted satellite to seek the nature and depth of its ocean
MARS FLIGHT MISSIONS (beyond 2005)		
Small (< $325 million)		
1	Mars Scout line	A competitively selected line of Mars missions similar in concept to Discovery
2	Mars Upper Atmosphere Orbiter	A spacecraft dedicated to studies of Mars's upper atmosphere and plasma environment
Medium (< $650 million)		
1	Mars Science Laboratory	A lander to carry out sophisticated surface observations and to validate sample return technologies
2	Mars Long-Lived Lander Network	A globally distributed suite of landers equipped to make comprehensive measurements of the planet's interior, surface, and atmosphere
Large (>$650 million)		
1	Mars Sample Return	A program to return several samples of the Red Planet to search for life, develop chronology, and define ground truth.

mantle. The South Pole-Aitken Basin, the largest impact structure known in the solar system, penetrates through the lunar crust. It is stratigraphically the oldest and deepest impact feature preserved on the Moon. The SPA-SR mission will help determine the nature of the differentiation of terrestrial planets and provide insight into the very early history of the Earth-Moon system. SPA-SR will also enable the development of sample acquisition, handling, and return technologies to be applied on other future missions.

Jupiter Polar Orbiter with Probes

The Jupiter Polar Orbiter with Probes (JPOP) mission will determine if Jupiter has a central core, a key issue that should help researchers decide between the two competing scenarios for the planet's origin. It will measure water abundance, which plays a pivotal role in understanding giant planet formation. This parameter indicates how volatiles (H_2O, CH_4, NH_3, and H_2S) were incorporated in the giant planets and, more specifically, the degree to which volatiles were transported from beyond Neptune to the inner solar system. The mission will probe the planet's deep winds to at least the 100-bar pressure level and may lead to an explanation of the extreme stability of the cloud-top weather systems. From its cloud-skimming orbit, JPOP will investigate the fine structure of the planet's magnetic field, providing information on how its internal dynamo works. Lastly, the spacecraft will repeatedly visit the hitherto-unexplored polar plasma environment, where magnetospheric currents crash into the turbulent atmosphere to generate powerful aurorae.

Venus In Situ Explorer

On descent, the Venus In Situ Explorer (VISE) mission will make compositional and isotopic measurements of the atmosphere and—quickly—of the surface. It will loft a core sample from Venus's hellish surface to cooler altitudes, where further geochemical and mineralogical data will be obtained. VISE will provide key measurements of the lower atmosphere and of surface-atmosphere interactions on Earth's would-be twin. The project will elucidate the history and stability of Venus's atmospheric greenhouse and its bizarre geological record. It will also advance the technologies required for the sample return from Venus expected in the following decade.

Comet Surface Sample Return

The Comet Surface Sample Return (CSSR) mission will collect materials from the near surface of an active comet and return them to Earth for analysis. These samples will furnish direct evidence on how cometary activity is driven. Information will be provided on the manner in which cometary materials are bound together and on how small bodies accrete at scales from microns to centimeters. By comparing materials on the nucleus against the coma's constituents, CSSR will indicate the selection effects at work. It will also inventory organic materials in comets. Finally, CSSR will yield the first clues on crystalline structure, isotopic ratios, and the physical relationships between volatiles, ice, refractory materials, and the comet's porosity. These observations will give important information about the building blocks of the planets.

Small Missions

Recommendations for small missions include a series of Discovery flights at the rate of at least one every 18 months and an extension to the Cassini-Huygens mission (Cassini Extended), presuming that the nominal mission is successful. Discovery missions are, by intent, not subject to long-term planning. Rather, they exist to create frequent opportunities to fly small missions addressing fundamental scientific questions and to pursue new research problems in creative and innovative ways.

Recommended Mars Flight Missions

For Mars exploration, the SSE Survey endorses the current science-driven strategy of *seeking* (i.e., remote sensing), *in situ measurements* (science from landers), and *sampling* to understand Mars as a planet, understand its astrobiological significance, and afford unique perspectives about the origin of life on Earth. The evolution of life and planetary environments are intimately tied together. To understand the potential habitability of Mars, whether it has or has not supported life, we must understand tectonic, magmatic, and hydrologic evolution as well as geochemical cycles of biological relevance. The return of materials from known locations on Mars is essential in order to address science goals, including those of astrobiology, and to provide the opportunity for novel measurements, such as age-dating, and ultimate ground truth.

Mars Science Laboratory

The Mars Science Laboratory (MSL) mission will conduct in situ investigations of a water-modified site that has been identified from orbit. It will provide ground truth for orbital interpretations and test hypotheses for the formation of geological features. The types of in situ measurements possible include atmospheric sampling, mineralogy and chemical composition, and tests for the presence of organics. The mission should either drill to get below the hostile surface environment or have substantial ranging capability. While carrying out its science mission, MSL should test and validate technology required for later sample return.

Mars Long-Lived Lander Network

The Mars Long-Lived Lander Network (ML^3N) is a grid of science stations that will make coordinated measurements around Mars's globe for at least 1 martian year. The highest-priority objectives for network science on Mars are the determination of the planet's internal structure, including its core; the elucidation of surface and near-surface composition as well as thermal and mechanical properties; and extensive synoptic measurements of the atmosphere and weather. In addition, atmospheric gas isotopic observations (to constrain the size of currently active volatile reservoirs) and measurements of subsurface oxidizing properties and surface-atmosphere volatile exchange processes will be valuable.

Mars Sample Return

Mars Sample Return (MSR) is required in order to perform definitive measurements to test for the presence of life, or for extinct life, as well as to address Mars's geochemical and thermal evolution. Further, characterization of Mars's atmosphere and now frozen hydrosphere will require highly sophisticated measurements and analytical equipment. To accomplish key science goals, samples must be returned from Mars and scrutinized in terrestrial laboratories**. For these reasons, the SSE Survey recommends that NASA begin its planning for Mars Sample Return missions so that their implementation can occur early in the decade 2013-2023**. Current studies of simplified Mars sample-return missions indicate that such missions are now within technological reach. Early on, NASA should engage prospective international partners in the planning and implementation of MSR.

Small Missions

Mars Scout missions are required in order to address science areas that are not included in the core program and to respond to new discoveries derived from current and future missions. A series of such small (<$325 million) missions should be initiated within the Mars program for flights at alternating Mars launch opportunities. This program should be modeled on the Discovery program.

Mars Upper Atmosphere Orbiter (MAO) is a small mission dedicated to studies of Mars's upper atmosphere and plasma environment. This mission would provide quantitative information on the various atmospheric escape

TABLE ES.3 Recommended Technology Developments

Category	Recommended Development
Power	**Advanced radioisotope power systems, in-space fission-reactor power source**
Propulsion	**Nuclear-electric propulsion, advanced ion engines, aerocapture**
Communication	**Ka band, optical communication**, large antenna arrays
Architecture	**Autonomy**, adaptability, lower mass, lower power
Avionics	**Advanced packaging and miniaturization**, standard operating system
Instrumentation	**Miniaturization**, environmental tolerance (temperature, pressure, and radiation)
Entry to landing	**Autonomous entry, precision landing**, and hazard avoidance
In situ operations	Sample gathering, handling, and analysis; drilling; instrumentation
Mobility	**Autonomy**; surface, aerial, and subsurface mobility; hard-to-reach access
Contamination	Forward-contamination avoidance
Earth return	**Ascent vehicles**, in-space rendezvous, and Earth-return systems

NOTE: Bold type indicates a priority item.

fluxes, thus quantifying current escape rates and providing a basis for backward extrapolation in our attempt to understand the evolution of Mars's atmosphere.

Technology Directions

A significant investment in advanced technology development is also needed for the recommended new and future flight missions to better succeed. Table ES.3 identifies a number of important areas in which technology development is appropriate. **The SSE Survey recommends that NASA commit to significant new investments in advanced technology so that future high-priority flight missions can succeed.**

RESEARCH INFRASTRUCTURE

In an era of competitively selected missions for space exploration, it will continue to be necessary to improve the technical expertise and infrastructure of organizations providing the vital services that enable the planning and operation of all solar system exploration missions.

For missions to be the most productive scientifically, a level of funding must be ensured that is sufficient not only for the successful operation of the flight but also for the contemporaneous analysis of the data and the publication of scientific results. Moreover, the SSE Survey's mission priorities rest on a foundation that must be secured and buttressed. This foundation includes fundamental research, technology development, follow-on data analysis, ground-based facilities, sample-analysis programs, and education and public outreach activities.

The entire pipeline that brings data from distant spacecraft to the broad research community must be systematically improved. Insufficient downlink communications capacity through the Deep Space Network (DSN) currently restricts the return of data from all missions, as, occasionally, does the DSN's limited geographical coverage. The DSN has to be continually upgraded as new technologies become available and system demands increase.

Once data are on the ground, they must be swiftly archived in a widely accepted and usable format. The Planetary Data System (PDS) should be included as a scientific partner at the very early stages of missions; it must be sized to accomplish its future tasks. In order to utilize the returned information effectively, analysis programs ought to be in place to fund investigators immediately upon delivery of ready-to-use data to the PDS. Data-analysis programs should be merged across lines (e.g., Discovery, New Frontiers) rather than being tied to individual missions.

A healthy research and analysis (R&A) program is the most basic requirement for a successful program of flight missions. **The SSE Survey recommends an increase over the decade in the funding for fundamental research and analysis programs at a rate above inflation that parallels the increase in the number of missions, amount of data, and diversity of objects studied.** Previous National Research Council (NRC) studies have shown that after a serious decline in the early to mid-1990s, the overall funding for R&A programs in NASA's Office of Space Science climbed in recent years to approximately 20 percent of the overall flight-mission budget.[1,2] Figures supplied by NASA's Solar System Exploration program show that the corresponding value for planetary activities is currently closer to 25 percent and is projected to stay at about this level for the next several years. The SSE Survey believes that this is an appropriate allocation of resources.

NASA's Astrobiology program has appropriately become deeply interwoven into the solar system exploration research and analysis program. **The SSE Survey encourages NASA to continue the integration of astrobiology science objectives with those of other space science disciplines. Astrobiological expertise should be called upon when identifying optimal mission strategies and design requirements for flight-qualified instruments that address key questions in astrobiology and planetary science.**

Ground-based telescopes have been responsible for several major discoveries in solar system exploration during the past decade. Moreover, many flight missions are greatly enhanced as a result of extensive ground-based characterization of their targets. **The SSE Survey recommends that NASA partner equally with the National Science Foundation to design, build, and operate a survey facility, such as the Large Synoptic Survey Telescope (LSST) described in *Astronomy and Astrophysics in the New Millennium,*[3] to ensure that LSST's prime solar system objectives are accomplished. Other powerful new facilities highlighted in that report—for example, the James Webb Space Telescope (formerly the Next Generation Space Telescope)—should be designed, where appropriate, to be capable of observing moving solar system targets. In addition, NASA should continue to support ground-based observatories for planetary science, including the planetary radar capabilities at the Arecibo Observatory in Puerto Rico and the Deep Space Network's Goldstone facility in California, the Infrared Telescope Facility on Mauna Kea in Hawaii, and shares of cutting-edge telescopes such as the Keck telescopes on Mauna Kea, as long as they continue to be critical to missions and/or scientifically productive.**

In anticipation of the return of extraterrestrial samples from several ongoing and future missions, an analogue to the data pipeline must be developed for cosmic materials. **The SSE Survey recommends that well before cosmic materials are returned from planetary missions, NASA should establish a sample-analysis program to support instrument development, laboratory facilities, and the training of researchers. In addition, planetary protection requirements for missions to worlds of biological interest will require investments, as will life-detection techniques, sample quarantine facilities, and sterilization technologies. NASA's current administrative activities to develop planetary protection protocols for currently planned missions are appropriate.**

Education and public outreach activities connect solar system exploration with its ultimate customers—the tax-paying public—and as such are an extremely important component of the program. Solar system exploration captures the imagination of young and old alike. By correctly illustrating the scientific method at work and demonstrating scientific principles, the planetary science community's efforts in communicating with students and lay people can be influential in helping to improve science literacy and education. In most implementations today, planetary scientists and education specialists work hand-in-hand to derive innovative and effective activities for communicating about solar system exploration with students, teachers, and the public. Although some problems remain, this program is well managed and is on a solid foundation.

CONCLUSIONS

For nearly 40 years, the U.S. Solar System Exploration program has led to an explosion of knowledge and awe with respect to our celestial neighborhood as ground-based telescopes and spacecraft have become much more capable while reaching out farther from Earth. We are now poised to address issues about our origins that have puzzled our forebears since civilization's beginning. Answers to profound questions about our origins and our future may be within our grasp. This survey describes an aggressive and yet rational strategy to deepen our analysis of such questions and finally resolve many long-standing mysteries during the next decade.

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Part One

Current Knowledge of the Solar System and Its Implications for Future Solar System Exploration

The five chapters that make up Part One of this report are the work of the Solar System Exploration Survey's (SSE Survey's) panels. These chapters provide a broad survey of the state of knowledge in each of the panels' particular scientific areas, identify key scientific questions, and make recommendations to the Survey's Steering Group on a wide variety of mission concepts to address these questions. This large body of work, together with the ad hoc community input received in various forms, is the basis for the integrated strategy for solar system exploration described in Part Two. Readers interested primarily in the final overall strategy may safely focus on Part Two and, as appropriate, use the material in Part One as a basic reference.

Although the SSE Survey encouraged use of a common format for each of the panel reports, the specific topics discussed by each panel led to some variations in presentation. Nevertheless, each panel chapter discusses the current understanding of, important questions for, and likely future avenues of progress in a small number of unifying scientific themes, and each panel identifies the most relevant ground- and space-based activities needed to advance understanding in its subject area. Each panel chapter prioritizes needed initiatives and makes final recommendations to the Steering Group.

The SSE Survey's Steering Group also requested that each panel identify the relative priorities among the important scientific questions by sorting them into one of three categories, in order of descending priority. This approach was implemented by asking whether the new knowledge gained from answering a particular question posed the possibility of—

1. Creating or changing a paradigm,
2. Having a pivotal effect on the direction of future research, or
3. Substantially strengthening the factual basis of current understanding.

1

Primitive Bodies: Building Blocks of the Solar System

The solar system's primitive bodies are those objects that have undergone a low degree of chemical and physical alteration since their condensation and aggregation from the solid and gaseous materials in the solar nebula some 4.6 billion years ago. These bodies are primarily small (less than a few hundred kilometers in size) and are found mostly in the vast region beyond the orbit of Mars. The primitive bodies (and materials) include asteroids, comets, small planetary satellites, the objects in the Kuiper Belt and the Oort cloud, Triton, Pluto, and Charon, and interplanetary dust (Figure 1.1).

While in the strictest sense "primitive" means *entirely* unchanged, the definition is flexible in planetary science and is used in a relative sense both in the research community and particularly in this report. All of these objects and materials have experienced some heating in the form of energy from the Sun and the decay of incorporated radioactive elements. Moreover, heat from collisions and tidal dissipation has caused some degree of change on the surface and in the interiors of many primitive bodies. Other factors affecting the surfaces and near subsurfaces of bodies without atmospheres include ultraviolet solar radiation, the solar wind, cosmic rays, and trapped particles in planetary environments.

Billions of years of bombardment by high-velocity meteoroids of every size (micrometers to kilometers) have affected every known surface in the solar system, causing physical and chemical changes at the exposed surface and creating soils and pulverized subsurface regions (regolith) by severe mechanical fracture.[1] Heat generated inside larger bodies has caused them to segregate the heavier materials (metals) from the lighter materials (rock and ice) in a process of differentiation. The easily evaporated materials (volatiles) have been partly lost from some small bodies by either internal or external heating and escape into space.

From the planetary science perspective, therefore, "primitive" means "substantially unaltered," primarily from a chemical point of view, even though some internal melting and differentiation may have occurred. Asteroids and comets are primitive, but the terrestrial and giant planets are not. The distinction is gray when highly differentiated asteroids, large planetary satellites, and Pluto are considered (although Pluto's bulk composition is

FIGURE 1.1 *(facing page)* A montage of spacecraft images of a small subset of the solar system's primitive bodies. *Clockwise from lower right:* 253 Mathilde, the nucleus of Comet 19P/Borrelly, the martian moons Deimos and Phobos, 433 Eros, 243 Ida, and 951 Gaspra. Courtesy of Peter Thomas, Cornell University.

almost certainly primitive). Objects excluded from this view of primitive bodies are all the major planets, the Moon, and the large satellites of Jupiter, Saturn, and Uranus.

UNIFYING THEMES FOR STUDIES OF PRIMITIVE BODIES

The planets originated from the accretion of solid and gaseous material in the solar nebula.[2] The first bodies to form in the nebula were millimeter- to kilometer-sized planetesimals.[a] Many were subsumed into the planets and their large satellites, but others remained behind and are known today as primitive bodies. Most of the objects considered primitive have not been substantially heated or otherwise changed in a chemical or physical sense since they formed, but others (e.g., certain asteroids and comets, Triton, Pluto, and Charon) have been heated to varying degrees.[3-5] Several populations of these primitive bodies remain in different regions of the solar system, notably the asteroid belt, the Kuiper Belt, and the Oort cloud.[6] Some members of these groupings have left their native regions through gravitational mixing; indeed, objects that originally formed in the outer planetary region and that were then expelled toward their current region by the gravitational action of the giant planets probably populated the entire Oort cloud.

Life on Earth is thought to be a product of the confluence of the necessary materials and an event of origin. The necessary materials include liquid water, carbon-bearing molecules, and energy, all of which were present on early Earth. Life arose early in our planet's history. One widely held view is that life arose at least 3.5 billion years ago, and perhaps as much as 3.8 billion years, but the origin event or events remain unknown and the exact timing is uncertain.[7] Organic molecular material carrying complex assemblages of carbon, hydrogen, oxygen, and nitrogen was delivered to the sterile early Earth by comets and asteroids, and some may also have been formed by impact events in the early ocean and atmosphere.[8]

Complex organic material exists in interstellar dust in our galaxy and others and thus predates the Sun and planets.[9,10] However, as researchers survey the primitive bodies and planets of the solar system, they find compelling evidence not only of the preservation of ancient organic matter but also of the formation and destruction of organic molecules in modern environments. Water, too, is common both in interstellar space and throughout the solar system, though its presence in the liquid phase depends on special circumstances of temperature and pressure. In several cases, however, even where water is not now a liquid, there is evidence that the liquid phase once existed. Thus, a search for organic matter in the solar system is an exploration of the range of environments in which life may have originated and a search for an understanding of our own origins as well.

Two clear themes therefore emerge as basic to study of the primitive bodies of the solar system:

- Primitive bodies as building blocks of the solar system, and
- The origins of organic matter that led to life on at least one planet.

The next two major sections expand upon these themes.

PRIMITIVE BODIES AS BUILDING BLOCKS OF THE SOLAR SYSTEM

Fundamental Issues

The fundamental questions concerning primitive bodies as building blocks of the solar system can be summarized as follows:

- Where in the solar system are the primitive bodies found, and what range of sizes, compositions, and other physical characteristics do they represent?
- What processes led to the formation of these objects?

[a]Definitions of technical terms and acronyms not explained in the text can be found in the glossary in Appendix E.

- Since their formation, what processes have altered the primitive bodies?
- How did primitive bodies make planets?
- How have they affected the planets since the epoch of formation?

Primitive bodies are highly varied in size, surface properties, composition, and probably origin. Apart from interplanetary dust, these bodies range in size from a few tens of meters to 2,500 km (Pluto and Triton). Some are snowy white, while others are charcoal black. Some have igneous and other minerals on their surfaces, while others have ices, and still others have combinations of ice and rock. Simple and complex organic chemicals are plentiful. The asteroids have highly varied compositions, with combinations of rock, metal, and organic compounds, while comets contain the same materials in a matrix of ices of various compositions.[11] Some asteroids have been thoroughly melted, while others have not. Some comets have been externally heated, with consequent changes in internal structure, but others appear to have been entirely unchanged since they formed.

Interplanetary dust near Earth appears to come from both comets and asteroids, and it contains minerals and organic solid matter.[12]

Triton, Pluto, Charon, and probably several large Kuiper Belt objects have icy surfaces and have probably been heated sufficiently for their interiors to differentiate.[13] Pluto and Triton have significant atmospheres. Triton is geologically active; Pluto and other bodies in this region of the solar system may also be active, and volatile transport clearly takes places on bodies such as Triton and Pluto. Their surfaces record their bombardment histories, hence the collisional history of the Kuiper Belt population.[14]

Important Questions

Questions that emerge from consideration of primitive bodies as building blocks of the solar system include the following:

- Are there Pluto-size and larger bodies beyond Neptune?
- How do the compositions of Pluto-Charon and Triton relate to those of Kuiper Belt objects?
- What are the basic physical properties (mass, density, size) of Kuiper Belt objects, Centaurs, and comets?
- What are the interior properties of all these bodies, and how do they differ from the surface compositions and properties? Are they differentiated?
- What are the surface properties and compositions of these bodies, and how do endogenous and exogenous processes affect them?
- Do Pluto and/or large Kuiper Belt objects show internal activity, as Triton does?
- What are the compositions of comet nuclei, and how do they relate to Kuiper Belt objects?
- What is the origin of the organic matter in carbonaceous meteorite parent bodies, and what are the parent bodies of the many different types?
- What organic materials occur in primitive bodies at various heliocentric distances?
- What is the origin of hydrated minerals in the meteorite parent bodies, and what do fluid inclusions in meteorites tell us about conditions in the solar nebula and parent bodies?
- What is the origin of micrometeorites?
- What are the albedo and color statistics of Centaurs, Kuiper Belt objects, and comets?

These questions are addressed and spelled out in more detailed questions in the remainder of this chapter.

Future Directions

A mission to Pluto-Charon and the Kuiper Belt can give critical, entirely new information on the physical properties of Pluto-Charon and members of the trans-Neptunian population. Despite their limitations relative to flight missions, additional Earth-based remote-sensing observations will give crucial new information on the compositions and other physical properties of primitive bodies in various populations. Such work requires the availability of the largest telescopes and most modern instrumentation. Radar observations of objects near Earth are critical to studying certain classes of asteroids and comets. The improvement of laboratory techniques for the analysis of planetary materials (meteorites and returned samples) offers the promise of new information and new perspectives on materials returned from primitive bodies. Spacecraft encounters with comets and asteroids will continue to expand our perspectives on the overall nature and variety of these objects, but there is an urgent need for samples collected from known sites on well-characterized objects to be returned to Earth for analysis. Curation and analysis of these materials are essential.

The Variety and Distribution of Primitive Bodies in the Solar System

More than 40,000 numbered asteroids are known, mostly orbiting the Sun between Mars and Jupiter but with a significant population in elliptical orbits that cross the paths of the inner planets, Mercury through Mars. Most of the asteroids accreted in the zone between Mars and Jupiter and occupy stable orbits, but some objects that are called asteroids (perhaps 5 percent) are former comets that originated elsewhere and are no longer active.[15] An unknown fraction of the asteroids are binaries, consisting of two separated objects orbiting a common center of gravity. Most of the meteorites that fall to Earth are fragments from collisions among the asteroids. The variety of meteorite types shows that there are many different kinds of asteroids.[16]

All four giant planets (Jupiter through Neptune) have families of distant, small satellites that have the appearance and other characteristics of asteroids; these are presumed to have originated elsewhere in the solar system and to have been captured subsequently by the gravity fields of the planets. The inner, small satellites of the giant planets are also considered primitive bodies, although they may have originated in the vicinity of their parent planet as part of the planet-forming process.

Two vast populations of primitive bodies exist beyond Neptune, both predicted from the orbital characteristics of comets; one of these is now the subject of vigorous exploration. Comets with periods greater than 200 years and with random orbital inclinations, of which 1,200 have been observed in the last two millennia, originate in the Oort cloud, a collection of more than a trillion icy bodies that orbit the Sun and extend almost halfway to the next nearest star.

Shorter-period comets, of which more than 200 are known, fall into two groups, the Halley-class comets that are probably captured from the Oort cloud comets, and the Jupiter-family comets that usually have orbits near the same planes as those of the planets and that originate in the Kuiper Belt, a donut-shaped distribution extending from the orbit of Neptune to at least 55 astronomical units (AU).[17] More than 500 individual objects in the Kuiper Belt have already been detected, and about 100,000 with sizes greater than 100 km are predicted to exist.[18] An unknown fraction of the bodies in the Kuiper Belt are binaries, mirroring the Pluto-Charon binary system.

Dust permeates the solar system. Some of it results from the activity of comets, some comes from the collisional disintegration of asteroids, and some is interstellar dust passing through the planetary region as the Sun and planets move among the stars. Some of the smallest dust grains condensed directly from gas in the solar nebula. Other interplanetary dust may have origins yet undiscovered and unexplored.[19]

Important Questions

Questions that emerge from the study of the variety and distribution of primitive bodies in the solar system include the following:

- Are there undiscovered populations, such as asteroids interior to Earth's orbit?
- What is the radial distribution of dust in the solar system?
- What is the frequency of binary systems among asteroids and trans-Neptunian objects?
- What is the orbital distribution of long-period and new comets?
- What are the orbital and size distributions of Centaurs and Kuiper Belt objects?

Future Directions

Surveys are in progress and planned for the detection of additional bodies in the known populations and for the exploration of their distributions and physical characteristics, but severe limitations are imposed by available facilities. Special search strategies must be developed for exploring each known population and for discovering other populations; proposed new ground-based facilities are well suited to the variety of searches required. The exploration of the dust distribution can be directly addressed by spacecraft carrying the appropriate instrumentation on many different trajectories through the solar system, as well as by missions designed specifically for dust studies.

Processes Leading to the Formation of Primitive Bodies

Planetesimals formed and grew in the solar nebula as interstellar dust, ice, and gas condensed into solid objects of tangible size. The planets formed by the accumulation of planetesimals at various distances from the Sun, but some planetesimals were captured after the planets formed, and became satellites.[20] Between Mars and Jupiter, heated and degassed planetesimals accumulated to become asteroids, some of which subsequently melted, either wholly or partially. At greater distances from the Sun, ices of several kinds from the primitive solar nebula were preserved as major constituents of most solid bodies. While some primitive bodies appear to have formed at their present heliocentric distances, other were gravitationally scattered by the planets. Some primitive asteroids, comets, and planetary satellites are fragments of larger objects produced by collisions among the bodies that originally accreted in the solar nebula.[21]

Important Questions

Questions that emerge with respect to processes leading to the formation of primitive bodies include the following:

- What was the chronology of formation of small bodies, and how and when did Pluto-Charon and some Kuiper Belt objects become binaries?
- Where in the solar nebula did the classes of primitive bodies form? Which were subsequently transported, and which remain in place?
- How did the Kuiper disk and the Oort cloud form, and what degree of compositional mixing is preserved? What forces caused the orbits of the Kuiper Belt objects to display such a wide range of inclinations and eccentricities?
- What was the balance between accretion and collisional destruction at various heliocentric distances during the formation of the solar system?
- Are there Trojan populations for Saturn, Uranus, and Neptune?
- When and how were the irregular satellites of the giant planets captured?

Future Directions

Dynamical studies with improved computational tools will continue to shed new light on problems of the formation and interactions of the primitive bodies of the solar system through time. Remote-sensing observations—particularly spectroscopy, radiometry, and photometry—of the physical properties of primitive bodies will help clarify their surface compositions, leading to improved taxonomy and a better understanding of their conditions of origin. Analysis of the surface structures seen in spacecraft images of key objects will improve our understanding of their fragmentation and cratering histories; such information bears directly on the dynamical history of primitive bodies in various regions of the solar system.

Physical Processes Affecting the Evolution of Primitive Bodies Since Their Formation

Primitive body surfaces, meteorites, and interplanetary dust particles carry information about some of the processes of space weathering and surface modification endured by these materials since the origin of the solar system.[22] These processes include solar heating and bombardment by cosmic rays and micrometeoroids, but other processes may have occurred. Some meteorites contain unaltered interstellar material that condensed before the formation of the Sun and planets, while other meteorites come from parent bodies that have been melted and differentiated, and still others show evidence of interaction with liquid water (some even contain inclusions of water).[23] Meteorites from primitive parent bodies are replete with complex organic molecular material and with water bound in the minerals. Collisions have played a commanding role in the evolution of primitive bodies, as evidenced by fragmented surface layers, irregular shapes, and fragmented soils preserved in some meteorites. Collisions also produce dust that is mixed in unknown proportions with the dust from evaporating comets; the combination of these materials forms the zodiacal cloud and the source of interplanetary dust particles (IDPs) collected in Earth's stratosphere for laboratory study.[24]

Important Questions

Questions that emerge from this discussion of the physical processes affecting the evolution of primitive bodies include the following:

- What processes in the solar nebula acted to alter presolar material?
- Are comets differentiated, and do they contain presolar material?
- What caused the differentiation of some asteroids?
- What are all of the space weathering processes that operate on the surfaces of bodies without atmospheres, and how have these processes varied over time?
- What is the time-history of collisional events and their consequences at various distances from the Sun?
- What are the thermal histories of all classes of comets; do they become extinct or dormant?
- Do Kuiper Belt objects exhibit evidence of transient atmospheres or epochs of internal activity?
- What roles did tidal activity, atmospheric escape, and internal activity play in generating the strongly dichotomous appearance of Pluto-Charon?
- Are Jupiter-family comets fragments of much larger Kuiper Belt objects, or are they still near their original size?

Future Directions

Missions to small bodies throughout the solar system, particularly missions that return samples, will illuminate the details of the evolution of primitive objects. Detailed analysis of IDPs and meteorites, using established techniques and those yet to be developed, will continue to elucidate some processes that occur in space, insofar as the record is preserved. Dust collected in space in the vicinity of known comets and from other locations in the solar system will significantly aid this study, while samples returned from the surfaces and subsurface layers of comets and asteroids will be critical for major advances. Proper curation and the development of new analytical techniques are critical to the understanding of returned samples. Theoretical studies of thermal histories of primitive bodies offer additional insights on several classes of these objects. Experiments with hypervelocity collisions will help clarify some physical processes, subject to the limitations of velocities that can be achieved in the laboratory.

Planets Formed by the Accumulation of Primitive Bodies

In terms of their sizes and compositions, the planets fall into four broad categories: the terrestrial planets (Mercury, Venus, Earth, Mars), the gas giants (Jupiter and Saturn), the ice giants (Uranus and Neptune), and the ice dwarfs (Pluto, plus the Kuiper Belt objects). All of the planets were formed by the accretion of smaller planetesimals that in turn condensed from the solar nebula at various distances from the forming Sun, but some of the planets may now occupy positions (heliocentric distances) different from the sites of formation.[25] The atmospheres of the terrestrial planets originated in whole or in part from the impact of volatile-rich primitive bodies.[26,27]

Important Questions

Questions that emerge with respect to the formation of planets by the accumulation of primitive bodies include the following:

- How did primitive bodies contribute to the volatile inventories of the terrestrial planets?
- Did organic matter delivered to early Earth (and other planets) by primitive bodies trigger the formation of life or provide the materials?
- When did Pluto and the Kuiper Belt objects form?
- How does accretion work, where do the materials come from, and what is the time scale?
- How much radial mixing of primitive material took place?
- What was the role of giant impacts in the formation of the planets and Earth's Moon?
- Why is there no planet between Jupiter and Mars?
- How large are the accreted bodies in the outermost solar system?
- What was the role of gas drag in the early solar system?

Future Directions

Dynamical studies with improved computational tools will continue to shed new light on problems of the formation and interactions of the primitive bodies of the solar system through time. Determinations of the densities and compositions of primitive bodies through spacecraft remote sensing techniques, and later by study of returned samples, will provide critical information on the materials from which the planets formed. Laboratory analysis to determine the isotopic signatures of samples returned from primitive bodies are essential to understanding the development of volatile inventories of the terrestrial planets.

Effects of Primitive Bodies on the Terrestrial Planets Since Their Formation

The cratering records on the Moon, the terrestrial planets, asteroids, and outer planet satellites reveal a history of bombardment throughout the solar system, from the time of formation to the present.[28] Meteorites, the tangible fragments of bombarding bodies, give information on the collisional fragmentation of primitive bodies and on the times of disruption and impact on Earth, all for relatively recent events. Interplanetary dust collected in the stratosphere and in space gives us a window on the generic composition of comets and some asteroids, but the exact source(s) of this material remain elusive.

Important Questions

Questions that emerge with respect to the effects of primitive bodies on the terrestrial planets since the planets' formation include the following:

- Do impacts lead to discrete and long-lasting changes in the surface-atmosphere regime?
- What volatiles and organics were delivered to the terrestrial planets?
- What fraction of impactors are comets vs. asteroids?

Future Directions

Computational studies of the interactions of impactors and their targets can further elucidate the nature of these processes in the early and modern solar system. Surveys of comets and asteroids will help clarify the flux of these objects in the planetary region. The physical properties of near-Earth objects must be measured to distinguish between comets and asteroids; this can be done with missions to these bodies and can be accomplished partly by radar and other remote-sensing techniques. Cometary dust must be distinguished from asteroidal or other (e.g., interstellar) dust. Expanded studies of the volatiles and organics in primitive meteorites and their parent bodies will bear on the questions of the materials delivered to the terrestrial planets.

PRIMITIVE BODIES AS RESERVOIRS OF ORGANIC MATTER: RAW MATERIALS FOR THE ORIGIN OF LIFE

The fundamental questions concerning the role of primitive bodies as reservoirs of organic matter (OM) in the solar system and in extrasolar planetary systems can be summarized as follows:

- What is the composition, origin, and primordial distribution of solid organic matter in the solar system?
- What is its present-day distribution?
- What processes can be identified that create, destroy, and modify solid organic matter in the solar nebula, in the epoch of the faint early Sun, and in the current solar system?
- How did organic matter influence the origin of life on Earth and other planets?
- Is organic matter similarly distributed among primitive bodies in other planetary systems?

Origin and Primordial Distribution of Solid Organic Matter in the Solar System

Carbon-rich molecular material condenses in the outflows from evolved stars and is injected into the interstellar medium. Modified by ultraviolet radiation and other processes, this material becomes enriched in complex organic molecules that coat silicate dust grains, but it also exists as submicron-size particles consisting entirely of interlocked ring structures.[29] High-resolution spectra with the Infrared Space Observatory (ISO) spacecraft recently showed that polycyclic aromatic molecules exist as a gas in the interstellar medium, together with condensed species on interstellar grains. The Sun and planets formed in a fragment of a giant molecular cloud enriched in this organic dust and gas. While some organic matter was destroyed in the solar nebula, new molecular material was created as chemical processes in the nebula occurred.[30] Later, additional organic molecular material may have formed on the parent bodies of the meteorites.[31]

Important Questions

Questions that emerge with respect to the origin and primordial distribution of solid organic matter in the solar system include the following:

- What is the composition and structure of primitive organic matter in the solar system?
- Where and under what conditions did organic matter originate?
- What are the relative fractions of organic matter in meteorites and comets that are interstellar and solar nebula in origin?
- Was primitive organic matter racemic?

Future Directions

Answers to the key questions listed above will come from the study of samples returned from well-characterized comets and asteroids and from continued astronomical observations of these objects as well as interstellar matter. The application of newly developed analytical techniques to existing and future collections of meteorites, micrometeorites, and stratospheric interplanetary dust particles will move this subject area forward. The analysis of dust collected in space is critical to these issues.

Present-Day Distribution of Organic Matter

Individual grains rich in organic matter are found in carbonaceous meteorites and interplanetary dust particles and are presumed to be a fundamental component of comets. The deuterium abundance in meteoritic and IDP organic matter is the same as is measured in the interstellar medium, providing a link to presolar matter in space.[32] There is spectroscopic evidence for the presence of complex organic material on several planetary satellites, Centaurs, and Kuiper Belt objects, and possibly certain asteroid classes. On icy satellites and in the rings of Saturn, the organic material may exist in very small quantities incorporated in water ice. On Pluto and Triton, photo processing of the methane ice may produce colored materials consisting of more complex organic chemicals.[33]

Important Questions

Questions that emerge regarding the present-day distribution of organic matter include the following:

- Which asteroids (or comets or Kuiper Belt objects) are the sources of the carbonaceous meteorites of various types, including the micrometeorites?
- What is the composition of organic matter in non-icy bodies?
- What are the compositions of organic matter that color some icy bodies, including Pluto and the Kuiper Belt objects?
- What are the sources of IDPs?

Future Directions

Answers to the key questions listed above will come from the in situ study of well-characterized regions on comet and asteroid surfaces, as well as the study of samples returned from comets and asteroids. Remote-sensing observations (spectroscopy) from missions to small bodies will contribute significantly to the understanding of their compositions. Continued studies of meteorites and interplanetary dust particles are critically needed. Astronomical observations of comets, asteroids, and planetary satellites from Earth and from space will expand our understanding of the relationships between meteorites and asteroids and will contribute to understanding the extent of organic material on primitive bodies, but they are unlikely to determine the organic material's composition.

Processes That Create, Destroy, and Modify Solid Organic Matter in the Solar Nebula

When simple gases or ices (water, ammonia, methane, hydrogen, and so on) are irradiated with ultraviolet light or a stream of atomic particles (electrons or protons), chemical changes occur that produce complex polymers and other solid residues that are strongly colored. When exposed to liquid water, such material produces amino acids and other complex molecules that occur in living systems.[34,35] The energy associated with impacts on planetary bodies can destroy some of this organic material, but it can create new species as well. In addition, radiation environments on the surfaces of planets and their satellites can both create and destroy complex organic molecules, but the detailed conditions and the balance between destruction and creation are unknown. Processes in space may affect the balance between the left-handed and right-handed mix of those organic molecules that have the property of chirality, and thus may have played a role in the origin of life on Earth, which is based on left-handed molecules.

Important Questions

Questions emerging from consideration of the processes that create, destroy, and modify solid organic matter in the solar nebula include the following:

- Are there unidentified processes that create and destroy organic matter?
- Do natural processes result in racemic mixtures of complex OM?
- What are the chemical details of the formation of macromolecular organic solids under different conditions and with different starting mixtures?
- What is the temporal history of organic formation in various environments in the solar system?
- What is the balance in the creation and destruction of OM in impacts and radiation environments?

Future Directions

Laboratory analysis of organic material in meteorites, IDPs, and returned samples from comets and asteroids is critical to making progress on the key questions listed above. Laboratory synthesis of complex organic with simulated planetary materials and environments will play a key role in understanding the genesis and evolution of this material in primitive bodies. Remote-sensing observations from missions to small bodies will contribute to understanding the processes that modify materials in the space environment.

How Did Organic Matter Influence the Origin of Life on Earth and Other Planets?

Organic molecular material, both simple and complex, existed in the solar nebula and was included in accreting planetesimals as ices and other solids of low volatility. Comets and Kuiper Belt objects are presumed to contain such material in their ices, while several classes of meteorites originating in the asteroid belt also contain large inventories of amino acids, carboxylic acids, and so on.[36] Asteroids and comets impacting Earth and other terrestrial planets during the late heavy bombardment delivered vast quantities of these materials, perhaps providing the raw materials for the origin of life.[37]

Important Questions

Questions that emerge from studies of how organic matter from primitive bodies influenced the origin of Life on Earth and other planets include the following:

- How does refractory OM vary among the comets, asteroids, planetary satellites, and other solar system bodies, and what does this tell us about the chemical environments in which it formed?
- What kind and quantities of OM delivered to early Earth and other terrestrial planets survived the impact and the planetary environments at that time?
- Did extraterrestrial organic matter trigger or provide the feedstock for early life on Earth?
- Where else in the solar system does life exist or has it existed?
- Could the terrestrial L-enantiomer preference result from the chirality of extraterrestrial OM?

Future Directions

While key questions can be formulated in the context of planetary science, the future directions in this area of how OM from primitive bodies influenced the origin of life on Earth and other planets are probably in the field of biology. In terms of the existence of fossil or contemporary life elsewhere in the solar system, exploration is the only tool available. Samples returned from primitive bodies will shed light on these questions in ways that no other source of information can.

Is Organic Material Similarly Distributed Among Primitive Bodies in Other Planetary Systems?

Many stars are surrounded by disks of dust showing structure suggestive of the presence of planets.[38] This dust is presumed to contain a mix of silicates and macromolecular carbon molecules preserved from the interstellar clouds in which the stars originated. One such star with a dust disk, β Pictoris, exhibits spectral flashes thought to result from the impact of comets into it. In addition, the recent detection of water in the outflow of a carbon-rich red giant star by the Submillimeter Wave Astronomy Satellite (SWAS) spacecraft suggests that a large number of comets are being vaporized in its extended atmosphere. Discoveries of Saturn- and Jupiter-size planets surrounding about 5 percent of solar-type stars in the Milky Way galaxy[39] further suggest that primitive comets and asteroids are relatively common in many star systems; they may be repositories of organic material preserved from the molecular clouds in which those stars and planets originated.

Important Questions

Questions that emerge from studies relating to the distribution of organic material among primitive bodies in other planetary systems include the following:

- Are there planets in the habitable zones around other stars?[b]
- What are the characteristic signatures of primitive body reservoirs around other stars?
- Is our assemblage of primitive bodies typical?

Future Directions

Numerical modeling and astrophysical observations of other star systems with indicators of the presence of planets will address the key questions listed above.

SPACE MISSIONS FOR THE EXPLORATION OF PRIMITIVE BODIES

While certain missions are expected to fall within the cost framework of the Discovery program, the Primitive Bodies Panel focused on missions that appear to exceed the $325 million Discovery-class limit but that are expected (when competed) to cost less than $650 million. These are termed "medium class." Missions that are expected to cost in excess of $650 million are called large-class missions.

Medium-Class Missions

Kuiper Belt-Pluto Explorer

A reconnaissance mission to two or more Kuiper Belt objects and Pluto-Charon is at the top of the Primitive Bodies Panel rankings because of its compelling importance to the scientific objectives identified by the panel. The core payload of the Kuiper Belt-Pluto (KBP) Explorer should include imaging and spectroscopy in the ultraviolet, visible, and infrared, uplink radio science, a suite of measurements of particles and plasmas, dust detectors, and a high-resolution imager.

[b]Throughout this report, the word "habitable" is used in a general sense meaning compatible with any kind of life. When "habitable" is used to mean compatible with human life, the text specifies that.

This mission will mark the beginning of the exploration of the third great geographic zone of the solar system, the region beyond the giant planets. The science objectives for a suite of Kuiper Belt objects that could be visited sequentially by relatively small changes in course as a first spacecraft flies deeper into the trans-neptunian region include (but are not limited to) the following:

1. Determination of the dimensions and shapes,
2. Determination of crater density,
3. Measurement of surface composition through imaging spectroscopy,
4. Detection of atmospheres,
5. Detection of evidence of any current geological activity (e.g., geysers), and
6. Measurement of dust density with increasing heliocentric distance in the Kuiper Belt.

For Pluto and Charon, the scientific objectives identified and prioritized by the Pluto Express Science Definition Team (SDT) should be met or exceeded.[40]

The science at Pluto and Charon is time-critical because of long-term seasonal changes in the surfaces and atmospheres of both bodies.

Surface Science Goals. The mandatory objectives of surface mapping and surface composition mapping of Pluto and Charon established by the SDT would be significantly compromised without an early mission.[41] This is due to Pluto-Charon's ongoing approach to a steep solstice geometry that increasingly hides in shadow large expanses of polar terrain on each object (~200,000 km^2 of terrain will be lost to imaging and spectroscopic mapping on Pluto alone for each year of arrival delay between 2015 and 2025). Beyond the proportional damage that this does to the global geology and composition mapping objectives that the SDT set for the mission, this loss of terrains will also severely affect the ability to answer key questions about the extent and nature of the polar volatile reservoirs on Pluto, the origin of the polar cap dichotomy on Pluto, and the possibility that volatiles capable of generating an atmosphere on Charon are sequestered in polar regions.

Atmospheric Science Goals. Concerning atmospheric science, Pluto's withdrawal from perihelion is widely anticipated to result in a substantial decline,[42] if not a complete collapse,[43] of its vapor-pressure-supported atmosphere.[44] Searches for an atmosphere around Charon, an extremely desirable mission objective called out in the SDT report, will also be adversely affected, or wholly lost, as will be the opportunity to study atmospheric transfer between Pluto and Charon—something unique in the solar system as far as we know. Other atmospheric science that will be lost at Pluto if the atmosphere collapses or significantly declines before mission arrival will be the ability to do the following, among other things:

- Test for hydrodynamic escape (a mandatory objective),
- Determine the base pressure and vertical haze/temperature structure of the atmosphere that has been under study since the 1980s (another mandatory objective),
- Pin down volatile transport rates (an extremely desirable objective), and
- Sample the atmospheric chemistry and the production of organics and nitriles during its maximum pressure (i.e., perihelion) state (another mandatory objective).

Comet Surface Sample Return—Samples from a Selected Surface Site

The Primitive Bodies Panel's second-ranked medium-class mission is the return of samples from a selected surface site on the nucleus of a comet. The science from this mission was considered more important than that from the Kuiper Belt-Pluto Explorer, but two fundamental differences arise related to readiness. First, there are several well-developed designs for KBP missions already available, whereas well-developed designs for a Comet Surface Sample Return (CSSR) mission are not available. Furthermore, there are engineering concerns about the viability of a surface sample-return mission related to the unknown nature of the cometary surface. While most cometary scientists think that the material is relatively weak and therefore easily sampled in a "grab-and-go" mode, only the Deep Impact mission is likely to resolve those engineering concerns as being either justified or not. This implies that the CSSR is most effectively begun after July 2005, when the results from Deep Impact will be known.

No other class of objects can tell us as much as samples from a selected surface site on the nucleus of a comet can about the origin of the solar system and the early history of water and biogenic elements and compounds. Only a returned sample will permit the necessary elemental, isotopic, organic, and mineralogical measurements to be performed. Although it is desirable to return a nucleus sample at a temperature sufficiently low to preserve the full suite of ices, the highest priority is given to a mission returning the full suite of organics and non-ice minerals together with water maintained as ice—a mission that is technically achievable in the next decade, and which the panel believes might be achieved in the medium-class category. High priority should be given to returning a sample from a comet that has been previously visited by spacecraft, or is characterized by the sample-collecting spacecraft itself, in order to permit the maximum interpretability of information to be obtained from the comet.

In the first sample-return mission from a comet, the material could be collected at one or more sites on the surface or in the near-surface layer, preferably in or near an active vent. It is recognized that this kind of mission does not address the full range of scientific issues that could be accomplished by a mission in which samples were collected from several regions on the nucleus, including the subsurface (by drilling), with the specimens returned at deep cryogenic temperatures. However, this more complete mission is thought to be outside the cost framework of the medium-class envelope. In any case, if a nucleus sample-return mission cannot be accomplished within the medium-class category, it should receive the highest ranking in the category of large missions. The panel strongly recommends that the entire Comet Surface Sample Return mission be competed through an Announcement of Opportunity, as was done for the KBP mission.

Trojan Asteroid/Centaur Reconnaissance

The Trojan Asteroid/Centaur Reconnaissance mission would send a KBP-like flyby reconnaissance spacecraft equipped with imaging, imaging spectroscopy, radio science, and, potentially, other instruments to make the first explorations of both a jovian Trojan asteroid and a Centaur. Beyond simply opening up these two new classes of primitive bodies to exploration, this mission has deep ties to understanding the origins of primitive bodies.

In particular, the Trojan flyby would sample primitive material from the jovian accretion region of the nebula; it would also allow an important recalibration of the bombardment flux on objects in the jovian system and would offer new insights into space weathering and other processes affecting asteroids, particularly in the main belt. The Centaur flyby would provide insights into the nature of the Kuiper Belt, the nature and origin of short-period comets and their parent bodies, and activity in distant comets.

Such a mission can be conducted with current technology, using a heavy-lift expendable launch vehicle (ELV) such as the Delta IV 4050H; if a Centaur inside ~6.5 AU is selected, it is possible to carry out this mission using large photovoltaic arrays, thereby avoiding the need for a radioisotope power supply. Such a mission would very likely also be capable of a main-belt asteroid flyby during its trip from the inner planets region en route to the Trojan zones.

Asteroid Lander/Rover/Sample Return

The Near-Earth Asteroid Rendevous (NEAR) mission to 433 Eros demonstrated that even small asteroids are covered with complex and substantial regoliths, which are heterogeneous in texture and detailed in composition (Figure 1.2). To understand the geologic evolution of asteroids, regoliths must be studied in detail, and their variability must be characterized both vertically and horizontally. NEAR has shown that the surfaces of asteroids can be so heterogeneous that it is difficult to identify a single "representative" locale. What is needed is the ability to land remote-sensing and analytical instruments and to provide the landed package with mobility in order to access a variety of geologic sites. The ability to return samples for detailed analysis on Earth is also essential. Such a mission would address the nature and time scales of geologic processes on asteroids and elucidate how

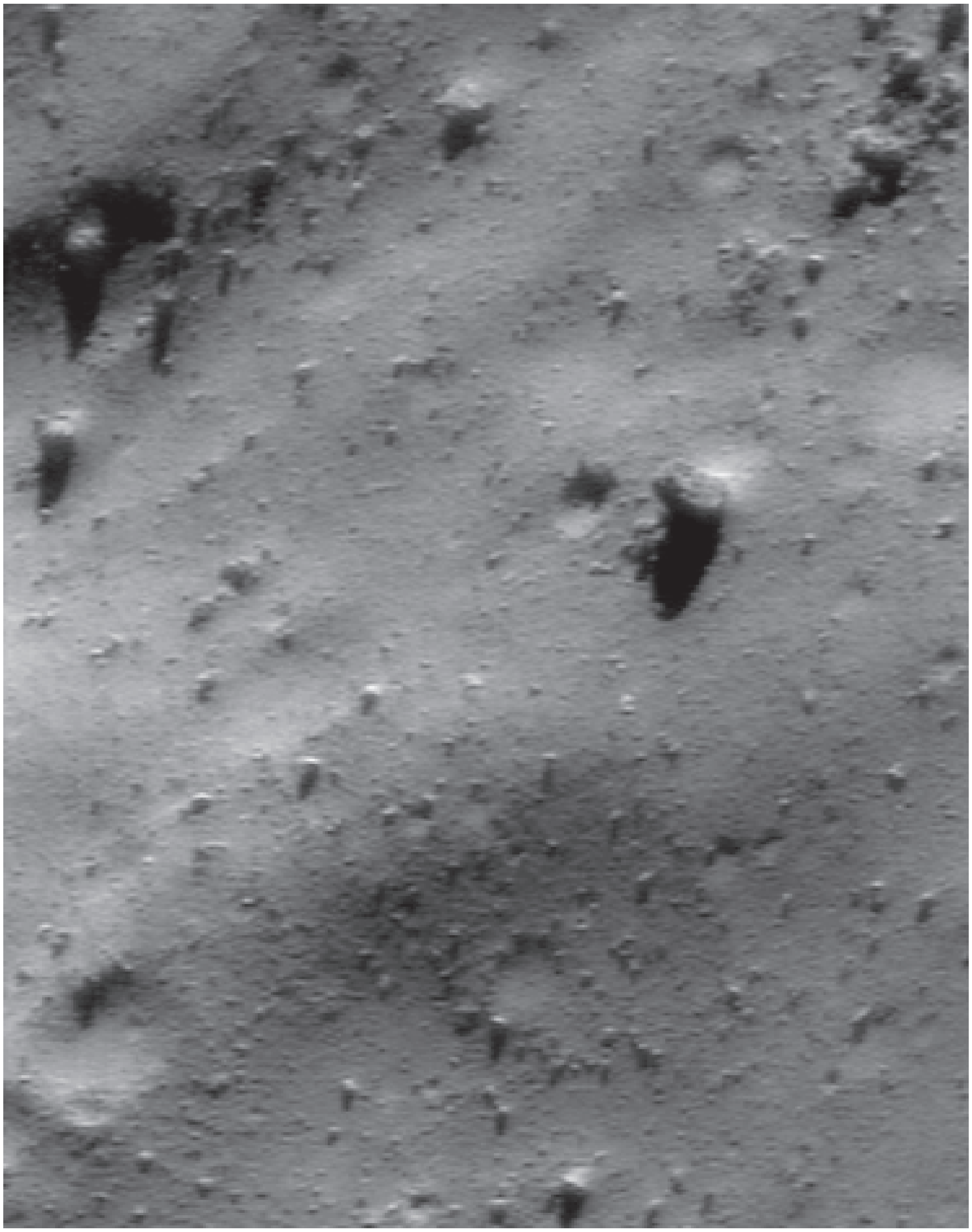
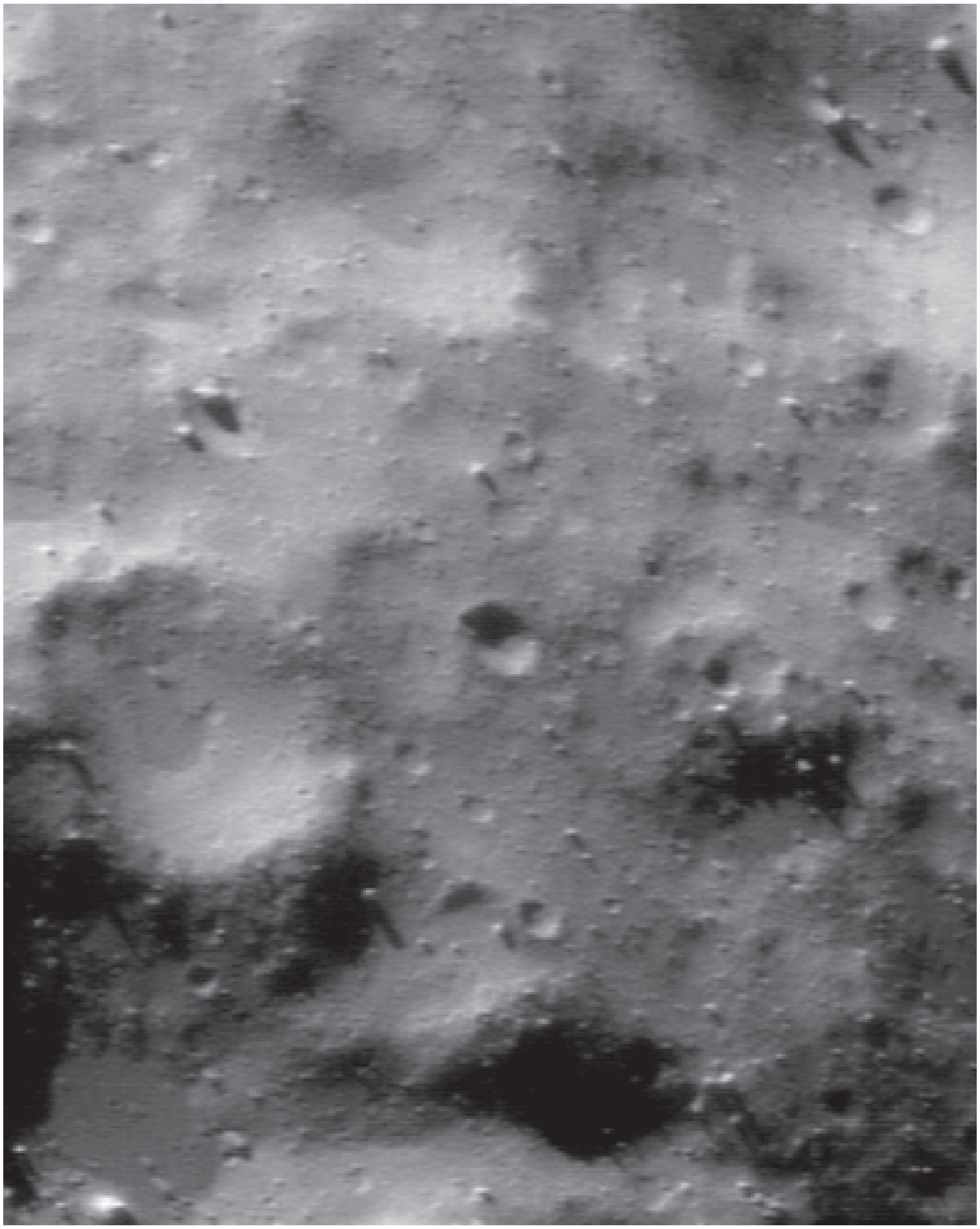


FIGURE 1.2 Though covered with rocks and boulders, the surface of asteroid 433 Eros appears to lack small craters. Those that are seen are muted, suggesting that the surface is covered with a blanket of regolith. These two images were taken by the NEAR Shoemaker spacecraft from an altitude of 38 km *(Right)* and 7 km *(Left)* and show features as small as 6 and 1.4 m, respectively. Courtesy of Applied Physics Laboratory.



these work to modify the texture and composition of the regolith. It would also provide a detailed compositional characterization of the asteroid.

To maximize the science return from such a mission, it is essential to select the most interesting locales on the asteroid, a goal that implies a global reconnaissance of the target body. In this context, a follow-up mission to asteroid 433 Eros should be given high priority. Eros represents a well-characterized, important target on which potentially interesting sites can be selected from existing data. Eros also represents a target that is relatively easy to reach dynamically and on which a successful landing has already been demonstrated.

Triton/Neptune Flyby

The Triton/Neptune Flyby mission would send a KBP-like flyby reconnaissance spacecraft, equipped with imaging, imaging spectroscopy, radio science, and potentially other instruments, to make a detailed second reconnaissance of the Neptune system. Using a Jupiter-gravity assist, such a mission could be launched in 2007, reaching Neptune in 2015. A Centaur flyby en route to Neptune is possible; a post-Neptune flyby of a KBO is also possible in an extended mission.

The primary target, the Neptune-Triton system, is scientifically rich (see Chapters 4 and 5 in this report) and would greatly benefit from a follow-up to Voyager. Such a flyby would bring to bear new technology instruments (e.g., infrared mapping spectroscopy) and would allow time-variability studies. This mission can be conducted with current technology, but it does require a radioisotope power supply. In addition to being deeply attractive to the primitive bodies community, such a mission would be appealing to those researchers interested in studies of the large satellites, planetary rings, and the giant planets—the latter, in particular, if it were feasible to include a Neptune atmospheric probe. Another feature of this mission commending it for additional study is that it would provide a means of sidestepping the return-to-Neptune cost and technology dilemmas imposed by current thinking about Neptune orbiter missions.

Large Missions

The panel identified a single high-priority mission in a cost category that, even with competition, is expected to exceed the cost of medium-class missions.

Comet Cryogenic Sample Return—Cold Samples from Depth

Because of the great importance of sample-return missions from comets to future progress in understanding the origin and development of the solar system and because of the limitations imposed by cost on a medium-class mission, the panel suggests that a larger-scale mission to one or more comets be undertaken. Such a mission would collect samples of a well-characterized comet nucleus from two or more selectable sites, both from the surface and from a depth on the order of 1 m. In order to preserve the full suite of volatile materials, the samples would be maintained at a temperature below 150 K through the return to Earth for analysis. A mission of this complexity requires further technological developments, particularly for drilling and sample collection and for cryogenic preservation and return to Earth.

KEY ENABLING TECHNOLOGIES FOR PRIMITIVE BODY EXPLORATION

The panel considered areas of technological development that are required to enable certain highly desirable missions. Those areas (in no particular order) are as follows:

- *Drilling on small bodies.* Techniques must be developed in order to collect samples of comets and asteroids below the exposed surface and deep into the region where volatiles may be retained. These samples will then be returned to Earth for analysis.

• *Cryogenic sample preservation and handling.* Techniques must be developed for the return of samples of comets to Earth for analysis. In order to retain the critical volatile components of a comet nucleus in samples collected below the exposed surface, the temperature of the sample must be maintained at less than 150 K during the collection, encapsulation, lift-off from the nucleus, and return and capture at Earth. Techniques for handling and analysis of cryogenic samples in the laboratory must also be developed.

• *Remote age determination and compositional analysis.* Techniques must be developed to be performed robotically at selected sites on primitive bodies (asteroids, comets, planetary satellites, and planetary surfaces) in order to provide cost-effective ways to explore the cosmochemical properties of critical bodies in the solar system.

• *Nuclear-electric propulsion.* This technology requires development so that it can be implemented late in this decade or as soon thereafter as possible.

KEY SUPPORTING RESEARCH AND FACILITIES

Near-Earth Objects

Near-Earth objects (NEOs) are asteroids, spent comets, and active comets that approach the Earth-Moon system and that in some cases may constitute an impact hazard of global proportions. Indeed, governmental studies in the United States, the United Kingdom, and elsewhere have requested surveys for near-Earth asteroids in search of objects that may constitute an impact hazard. More than a statistical study, governments desire a catalog of potential impactors that would produce global catastrophes or widespread damage on smaller scales in the next century. Surveys in progress have identified an estimated 50 percent of the near-Earth asteroids and extinct comets 1 km and greater in size, and very roughly 10 to 15 percent of such bodies 0.5 km in size. Approximately 340 (as of November 2001) of these come especially close to Earth and are cataloged as Potentially Hazardous Asteroids. The number of new comets with impact potential is large and unknown.

Important scientific goals are associated with the NEO populations, including their origin, fragmentation and dynamical histories, and compositions and differentiation. These and other scientific issues are also vital to the mitigation of the impact hazard, as methods of deflection of objects potentially on course for an impact with Earth are explored. Information especially relevant to hazard mitigation includes knowledge of the internal structures of near-Earth asteroids and comets, their degree of fracture and the presence of large core pieces, the fractal dimensions of their structures, and their degree of cohesion or friction.

The scientific goals of near-Earth object studies for the objectives of both pure science and science for the public good should be addressed in an aggressive, multidimensional program of detection and physical studies with Earth-based telescopes, including radar, and perhaps telescopes in space. In addition, high priority is given by the panel to missions to representative objects (e.g., 433 Eros) to establish their physical properties, as noted above. Samples returned from near-Earth objects are a critical component of these objectives. Accordingly, the Primitive Bodies Panel recommends a medium-class mission to land on an asteroid, possibly 433 Eros, collect samples from several well-characterized locations, and return them to Earth for analysis. Discovery-class missions for the reconnaissance of additional near-Earth asteroids and extinct comets are also recommended. The panel further recommends that dedicated and powerful ground-based facilities for the detection and physical study of near-Earth objects be implemented, together with the data-handling and data-analysis capabilities that large-scale surveys will require. Additionally, adequate support is critically needed for the analysis of data from missions to near-Earth objects, as well as theoretical studies of the cosmochemical, geophysical, geological, and dynamical evolution of such objects and their precursor bodies.

Earth-Based Telescopes

In the decade under consideration, ground-based telescopes will continue to play key roles in the detection and physical study of primitive solar system bodies. Asteroids near Earth and in the main belt are found and studied with ground-based telescopes, as are Kuiper Belt objects, Centaurs, distant comets, and most planetary satellites. It is essential that ground-based telescopes suited to all-sky surveys and other detection strategies be included as an integral component of the next decade of solar system exploration. Equally important are telescope facilities capable of spectroscopic, photometric, radiometric, and radar investigations of known and newly discovered small bodies in the solar system. With some existing and proposed facilities, the objectives of detection and physical studies can be met with the same telescope equipped with a variety of supporting instrumentation.

Earth-based facilities—a broader term encompassing not only ground-based telescopes but also airborne telescopes (notably, the Stratospheric Observatory for Infrared Astronomy [SOFIA]) and near-Earth spaceborne telescopes (e.g., the Space Infrared Telescope Facility [SIRTF], the Hubble Space Telescope [HST], and the James Webb Space Telescope [JWST])—will play critical roles in the study of solar system bodies in wavelength regions inaccessible from the ground, and these must be supported. Many solar system observations impose special requirements on telescopes (for example, because of moving targets, faint objects near bright planets, and the need for high definition), and it is important that newly defined projects for telescopes on all platforms include the technological options that will enable observations of solar system bodies.

Telescopes on the ground, in the air, and in space afford observations of vastly more objects than can ever be visited by spacecraft. They not only enable us to select appropriate targets for spacecraft visits, but also let us put into context the information gained from expensive and infrequent space missions to asteroids, comets, and other primitive solar system bodies. Numerous examples could be given of the critical value of mission support afforded by observations with telescopes of various kinds; a few are mentioned here to help underscore the breadth of the concept of "mission support":

- The Galileo probe entered Jupiter's atmosphere in an anomalously cloud-free region whose strong infrared emissions were detected by NASA's Infrared Telescope Facility (IRTF) on Mauna Kea. Without this information, the context of the information relayed by the probe would have been lost.
- The Kuiper Belt-Pluto Explorer mission currently under development is intended to visit Kuiper Belt objects that probably have not yet been discovered. The eventual targets will be detected by ground-based surveys of the appropriate volume of space.
- A mission to a presumed organic-rich asteroid will have to be targeted at an object that has been observed and classified from Earth-based observations.
- A mission to a dynamically new, inbound comet would require either dramatically improved discovery capability for comets at large heliocentric distance or a mission "ready to go," either on the ground or already in heliocentric orbit.

This broad definition of mission support challenges NASA to be forward-thinking and inclusive, so that ground-based telescopes can find targets, define basic parameters, and motivate key science questions that can only be addressed by spacecraft.

Many of the observational requirements for solar system objects are fully as challenging as the faintest and most difficult objects in modern astrophysics and thus require very large apertures, highly sensitive detectors, versatile spectrographs, and other supporting instrumentation, often with special features to enable observations of moving targets and faint targets that are nearby bright planets.

The SSE Survey's Primitive Bodies Panel endorses the concept of a large telescope capable of an all-sky search strategy that would reveal large numbers of near-Earth objects as well as trans-Neptunian objects, thus completing the surveys of these objects to a brightness level much beyond the current capabilities.

The Primitive Bodies Panel also endorses a telescope that would enable the physical study of such objects by spectroscopic and photometric techniques. The panel heard recommendations for the Large Synoptic Survey Telescope (LSST) and the Next Generation Lowell Telescope (NGLT), both of which enable surveys and physical observations at some level that exceeds current capabilities. Other options, including the Panoramic Optical Imager concept, should be explored and a choice made that NASA can support in the next decade.

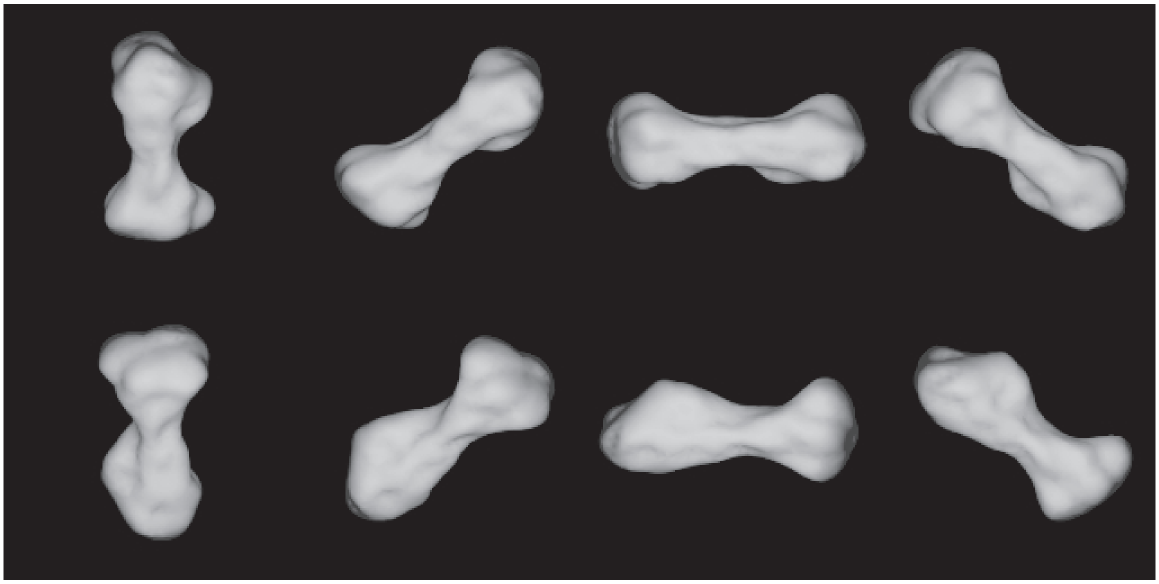


FIGURE 1.3 Multiple radar observations of the main belt asteroid 216 Kleopatra revealed the rotation of this unusual object. At the time that these observations were made with the planetary radar facility at the Arecibo Observatory in Puerto Rico, Kleopatra was some 171 million kilometers from Earth. Spectroscopic studies indicate that this 217-km-long object has a metallic composition. Courtesy of National Aeronautics and Space Administration/Jet Propulsion Laboratory.

Support for Existing Facilities

Planetary Radar Facilities. The panel heard a presentation on the status and future of the planetary radar facilities at Arecibo, Puerto Rico, and Goldstone, California, as they are used for studies of small solar system bodies (Figure 1.3). These highly productive facilities provide unique information on the shapes and sizes, regolith properties, and occurrence of binaries among near-Earth objects, and provide critical astrometry for orbit predictions. Both facilities are working at their limits in terms of equipment and personnel. The data-acquisition systems at both facilities urgently need upgrading, and the staffing is insufficient to handle the observing workload imposed by the increasing numbers of near-Earth objects being discovered and requiring follow-up observations. Replacements for near-term retirement of critical technical staff are urgently needed. The panel recommends that both of these important facilities be supported and upgraded as needed, for the unique information that radar observations of small solar system bodies provide.

The NASA Infrared Telescope Facility. The IRTF, mentioned above, contributes to a wide spectrum of solar system and astrophysics investigations by U.S. and foreign astronomers and makes a special contribution to the study and characterization of near-Earth objects. In particular, in a focused effort on small bodies and with dedicated observing programs, instrumentation, and rapid response time, the IRTF will contribute critical information for planning space missions to comets and asteroids. Even in an epoch of 6- to 10-m telescopes, the contributions of the 3-m-aperture IRTF are very important to the next decade of solar system studies, and the panel recommends that requested upgrades to the facility be made to ensure operations at a state-of-the-art level.

The Keck Telescopes. Some 15 percent of the observing time on the twin 10-m telescopes at the Keck Observatory on Mauna Kea is available for studies in areas selected by NASA. These studies are defined in a priority order with interferometry first, detection of extrasolar planets second, and general solar system astronomy third. The result is that very little time is available for general studies, for example, of KBOs. The Primitive Bodies Panel recommends that NASA's commitment be sustained at a high enough level that scientifically important problems in solar system astronomy, such as physical characterization of KBOs, can be carried out with this facility.

Laboratory Facilities for Returned Samples. It is critically important to prepare for the sample returns from the Stardust, Genesis, and Muses-C and the anticipated returns from Mars and a comet nucleus by the establishment of a realistic laboratory instrument-development program. Existing programs of this nature are dramatically underfunded. Initial funding should be aimed primarily at the development of new analytical technologies, with the most urgent need being for the development of organic chemistry microanalysis. As new techniques are established, the program priorities should shift to upgrading U.S. laboratories with the new analytical equipment.

Laboratory Facilities for the Study of Planetary Materials

Laboratory studies in support of observational studies, and particularly NASA planetary missions to planets, comets, and asteroids, are critical to the correct and complete interpretation of the data acquired at great expense. Such work is inadequately supported either in existing laboratory facilities or through the creation of new laboratories. The Primitive Bodies Panel recommends that as long as sample-return missions are in the mission plan, there is a continuing need for upgrades to the equipment used for analyzing the samples at levels currently in NASA's Sample Return Laboratory Instruments and Data Analysis program.

Curation

A critical necessity in preparation for the sample returns from the Stardust, Genesis, and Muses-C and the anticipated returns from Mars and a comet nucleus is support for sample curation and handling at a significantly increased level over what exists today. The proper preservation of each returned sample for future investigations is of paramount importance. The samples returned from each object will have particular handling and storage demands, which must be addressed by separate, specialized facilities. The funding for these facilities, including long-term operating costs, cannot realistically come from each mission's budget. In particular, development is required in the areas of cryocuration, robotic sample handling, and biological quarantine. The panel recommends that the facilities required for the proper analysis and curation of returned samples be developed and supported.

KEY QUESTIONS AND MEASUREMENT OBJECTIVES

The important questions identified in each of the thematic sections above are merged here into key scientific questions that are amenable to solution in the decade under consideration by a series of space missions and surveys of the solar system from Earth-based observatories, as well as expanded laboratory facilities. These questions are presented here, condensed and reframed, in three categories of expected impact. The panel measures the impact of a question by asking whether its answer has the possibility of creating or changing a paradigm, whether the new knowledge might have a pivotal effect on the direction of future research, and to what degree the knowledge that might be gained would substantially strengthen the factual basis of our understanding. These measures of merit are listed in the order of the priority that the panel associates with them.

Primitive Bodies As Building Blocks of the Solar System

Potentially paradigm-altering questions about primitive bodies as building blocks of the solar system include the following:

- What is the population structure of the solar system?
- What is the nature of Kuiper Belt objects?
- What is the formation history of the trans-Neptunian region?
- Where in the solar system did building blocks form; which were transported and which were not?

Questions of pivotal importance include the following:

- How do compositional differences between the Oort cloud and the Kuiper Belt bodies relate to their sites of origin?
- Are small, distant bodies such as Kuiper Belt objects, Pluto, and Charon geologically active today?
- What is the nature of binary objects in the solar system, and what do they tell us about formation history?
- What processes modify the surfaces of all categories of building blocks?

Foundation-building questions are as follows:

- How do colors and albedos of small bodies relate to their compositions and histories of alteration by various processes since their origin?
- What roles did various dynamical processes play in the origin and evolution of the primitive bodies in the solar system, and what were the time scales?
- What are the orbital distributions of long-period and new comets, and how have these distributions evolved over the age of the solar system?

Primitive Bodies As Reservoirs of Organic Matter

Potentially paradigm-altering questions about primitive bodies as reservoirs of organic matter include the following:

- What are the compositions and origins of the organic and volatile materials in primitive bodies?
- How is organic matter distributed throughout the solar system?
- What is the chemical and isotopic composition of cometary surface materials?
- What are the physical and chemical/isotopic properties of comet nuclei, and do they vary with depth?

Questions of pivotal importance include the following:

- Did organic matter from comets and meteorites provide the feedstock for the origin of life on Earth?
- What are the parent bodies of the carbonaceous meteorites, interplanetary dust particles, and micrometeorites?

Foundation-building questions are as follows:

- What are the processes by which organic material forms on the surfaces of icy and other primitive bodies in the current epoch?
- What is the thermal and aqueous alteration history of the parent bodies of the organic-rich primitive meteorites?

Table 1.1 shows the themes and questions identified by the Primitive Bodies Panel and the impact of specific missions and surveys toward their resolution.

The two themes around which this chapter is organized—primitive bodies as building blocks of the solar system, and organic matter in the solar system as materials for the origin of life—are equally important and urgent. The key questions for each theme are listed in the order of importance in the sense of representing the steps needed to address the themes. Table 1.1 represents the Primitive Bodies Panel's best judgment of the extent to which each

TABLE 1.1 Primitive Bodies: Relationship of Themes, Key Scientific Questions, and Mission Possibilities

Class of Question	Theme and Key Questions	Current Missions	KBP[a]	First CNSR[b]	Trojan/ Centaur Flyby	Primitive NEO[c] Return	Survey and Follow-up Telescopes
	Theme 1. BUILDING BLOCKS OF THE SOLAR SYSTEM						
Paradigm altering	1. What is the population structure of the solar system?		xxx		x		xxx
	2. What is the nature of the KBOs?		xxx	x	xx		xx
	3. What is the formation history of the trans-Neptunian region?	x	xxx	xx	x		xx
	4. Where in the solar system did building blocks form; which were transported and which were not?	xx	xx	xx	xx	x(?)	xx
Pivotal	1. How do compositional differences between the Oort cloud and the Kuiper Belt bodies relate to their sites of origin?	x	x	x	x		x
	2. Are small, distant bodies such as KBOs, Pluto, and Charon geologically active today?		xxx		x		x
	3. What is the nature of binary objects in the solar system, and what do they tell us about formation history?		xx				xx
	4. What processes modify the surfaces of all categories of building blocks?	xx	xx	xxx	xx	xxx	
Foundation building	1. How do colors and albedos of small bodies relate to their compositions and histories of alteration by various processes since their origin?	x	xx	xx	xx	xx	xx
	2. What roles did various dynamical processes play in the origin and evolution of the primitive bodies in the solar system, and what were the time scales?		xx		xx	x	xx
	3. What are the orbital distributions of long-period and new comets, and how have these distributions evolved over the age of the solar system?		x				x
	Theme 2. ORGANIC MATTER IN THE SOLAR SYSTEM: MATERIALS FOR THE ORIGIN OF LIFE						
Paradigm altering	1. What are the compositions and origins of the organic and volatile materials in primitive bodies?	xx	x	xxx	x	xxx	x
	2. How is organic matter distributed throughout the solar system?	xx	xx	xx	xx	xx	xx
	3. What is the chemical and isotopic composition of cometary surface materials?	xx		xxx	x		x
	4. What are the physical and chemical/isotopic properties of comet nuclei, and do they vary with depth?	xx		xxx		x (?)	
Pivotal	1. Did organic matter from comets and meteorites provide the feedstock for the origin of life on Earth?	xx		xx	x	xx	x
	2. What are the parent bodies of the carbonaceous meteorites, IDPs, and micrometeorites?	x		x	x	x	
Foundation building	1. What are the processes by which organic material forms on the surfaces of icy and other primitive bodies in the current epoch?	x	xx	x	x	xx	x
	2. What is the thermal and aqueous alteration history of the parent bodies of the organic-rich primitive meteorites?			x	x	xxx	x

NOTE: xxx = breakthrough level of advance, xx = significant advance in understanding, x = some advance in understanding, and x(?) = requires that target turns out to be an extinct comet.
[a]Kuiper Belt-Pluto Explorer. [b]Comet Nucleus Sample Return. [c]Near-Earth object.

mission or set of missions will advance current knowledge regarding the key (paradigm-altering) questions. The magnitude of the advance is indicated by the number of "x's" in a nonlinear fashion (i.e., xxx > (xx + x)). Similar rankings for different missions on a particular question do not imply scientific redundancy because the questions are multidimensional.

RECOMMENDATIONS OF THE PRIMITIVE BODIES PANEL TO THE STEERING GROUP

In establishing a ranked list of missions for the continued exploration of primitive bodies, the panel took into account various factors related to missions that are technically feasible in the decade 2003-2013. The following factors were included:

- The paucity of radioisotope power systems currently available,
- The fact that no major new technology developments were required, and
- The need for focused scientific objectives.

The ranked mission set that the Primitive Bodies Panel recommends is as follows:

1. *Kuiper Belt-Pluto Explorer.* Such a mission can be accommodated within the cost range of a medium-class program.
2. *Comet Nucleus Sample Return.* A mission of limited scope (e.g., Comet Surface Sample Return) could be included in the medium-class cost category. A larger-scale mission with greater capability (e.g., Comet Cryogenic Sample Return) would fall into the category of a large mission. Depending on phasing, both are desirable.
3. *Trojan Asteroid/Centaur Reconnaissance.*
4. *Asteroid Lander/Rover/Sample Return.*
5. *Triton/Neptune Flyby.*

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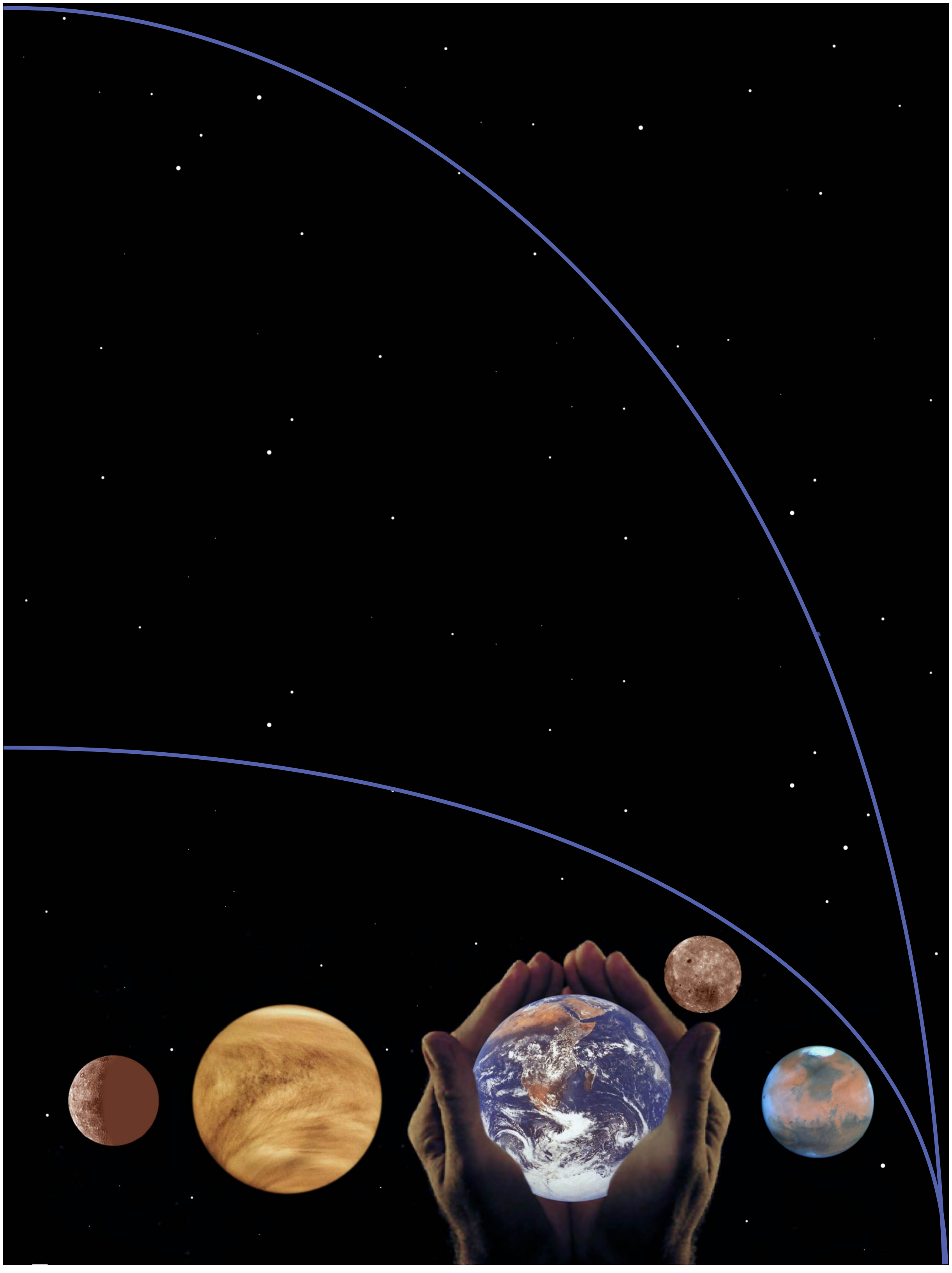

2

Inner Solar System: Key to Habitable Worlds

The inner planets provide a unique opportunity to study the processes that lead to habitable worlds. Venus, Mercury, Mars, and the Moon (Figure 2.1) each hold clues to different aspects of the origin of the planets and habitable environments in the inner solar system. The Moon and Mercury preserve records of past events that are largely erased on Earth and Venus. In many ways, Venus is Earth's twin in the solar system, and it provides a natural laboratory for understanding the evolution of Earth-like planets and their atmospheres, including how Earth's atmosphere might change in the future. Mars shows evidence for substantial climate change, which could reflect processes that influenced all of the inner planets.

UNIFYING THEMES FOR STUDIES OF THE INNER PLANETS

At the most fundamental level, Earth is unique. Through the study of other objects in the inner solar system, it is now understood that Earth as a habitable planet is the result of a series of stochastic events that occurred over its 4.6-billion-year history. The terrestrial or "Earth-like" planets exhibit common geologic processes that both reflect and determine their fate. Each of our neighbors is the result of planetary-scale processes operating in the inner solar system with different boundary conditions.

As the initial reconnaissance of our solar system draws to a close, the scientific goals for exploration are changing. The initial exploratory steps were driven by the intense public and scientific interest in glimpsing new worlds for the first time. As articulated in this report, however, a new paradigm for solar system exploration is emerging, one that seeks to address fundamental questions about our place in the universe. Thus, the unifying themes of the next decade of exploration of the inner planets focus on the following:

- *The past: Where did we come from?* What led to the unique character of our home planet?
- *The present: What is going on?* What common dynamic processes shape Earth-like planets?
- *The future: Where are we going?* What fate awaits Earth's environment and those of the other terrestrial planets?

FIGURE 2.1 *(facing page)* How do the compositions, internal makeup, and geologic history of the planets explain the formation and sustainment of habitable planetary environments? This image shows, from the left, Mercury, Venus, Earth and the Moon, and Mars as they appear in slightly enhanced natural color. Full images of Mercury do not exist. The farside of the Moon is shown. Courtesy of Vesper/Goddard Space Flight Center and Peter Neivert.

Exploration of the inner solar system is vital to understanding how Earth-like planets form and evolve and how habitable planets may arise throughout the galaxy. Understanding processes on a planetary scale—volcanism, tectonism, impact bombardment, evolution of the atmosphere and magnetosphere, and development and evolution of life—requires comparative study of the planets closest to Earth in order to know the effects associated with size, distance from the Sun, composition, and the style of dissipation of internal energy over time. Comparative study of the inner planets shows the importance of a large moon in making Earth unique and perhaps uniquely suitable for life. One of the great advances of geoscience has been to recognize that present-day Earth represents just one step in a progression of changes driven by a complex set of interrelated planetary factors. Coupled with this recognition is the revelation that Earth's atmosphere and biosphere are fragile entities readily perturbed by planetary-scale processes. Much remains to be learned from the other terrestrial planets, where similar processes have produced vastly different results.

In this context, several broad questions that are fundamental to the human quest for understanding our place in the universe can be addressed only by a detailed exploration of the inner planets:

- *Paradigm-altering question.* What geologic and atmospheric processes stabilize climate?
- *Pivotal question.* How have large impacts affected the course of planetary evolution?
- *Foundation question.* How do the compositions, internal makeup, and geologic history of the planets explain the formation and sustainment of habitable planetary environments?

The past four decades of exploration, observation, and research have provided glimpses of Mercury, a first-order understanding of the Earth-Moon system that laid the foundation for much of planetary science, and tantalizing insights into the nature of the atmosphere, surface, and interior of Venus (Figure 2.2). Substantial advances have been made in the exploration of Mars from orbit and at three landing sites for in situ measurements.[a] Clearly, many fundamental questions remain unresolved. Future progress will require detailed study of Earth-like planets and of the constraints on how habitable worlds arise, evolve, and are sustained. The next decade holds immense promise for major advances in answering these questions.

The next three major sections present a broad survey of the state of knowledge of the inner planets in the context of specific scientific issues relating to the themes outlined above. The significance of each issue is explained, and a summary is given of relevant scientific progress to date. Important questions are identified, and future directions for the Solar System Exploration program are then outlined. By their very nature, several of the most fundamental science investigations require commitment to a long-term integrated approach of observation, measurement, and analysis.

WHAT LED TO THE UNIQUE CHARACTER OF OUR HOME PLANET?

The factors leading to Earth's unique characteristics and, by extension, the unique characteristics of the other inner planets may be organized as follows:

- The bulk compositions of the inner planets and their variations with distance from the Sun;
- The internal structure and evolution of the core, crust, and mantle;
- The history and role of early impacts; and
- The history of water and other volatiles and the evolution of inner planets' atmospheres.

Recent progress in studies of each, likely future directions for research, and the important questions that need to be addressed are outlined below.

[a]Given the scientific and programmatic importance of Mars exploration, detailed considerations and discussions of the subject are deferred until Chapter 3.

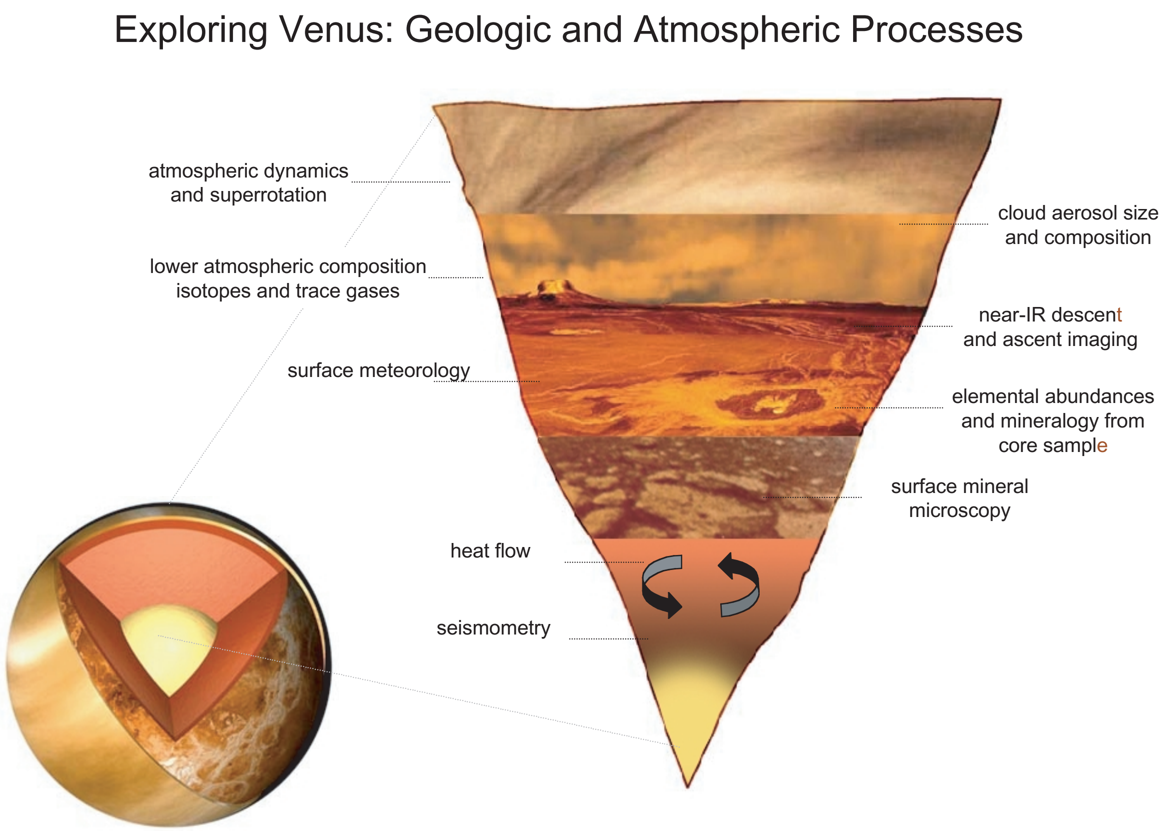

FIGURE 2.2 A slice into Earth's sister planet Venus illustrates the unknown nature of the structure and state of the interior; the composition and history of materials at the surface; and the composition, circulation, and evolution of the atmosphere. Also indicated are some of the means by which these unknowns may be investigated. Courtesy of Jet Propulsion Laboratory, E. Stofan, and M. Bullock.

Bulk Compositions of the Inner Planets and Their Variation with Distance from the Sun

A fundamental constraint on the formation of Earth-like planets is whether the inner planets are random accumulations of specific building blocks or whether a systematic cosmochemical trend related to distance from the Sun exists. The bulk compositions of the inner planets resulted from early nebular processes, planetary accretion, and the removal or addition of material following accretion. The concentrations of volatile elements resulted from primary nebular processes (e.g., condensation), secondary processes (e.g., solar-wind erosion), late addition from comets, or a combination of these processes. Determining the bulk compositions of the terrestrial planets is key to understanding the roles of these major formative processes. Especially important are the noble gases and their isotopes, which record early planetary formation processes because they remain chemically inert.

Recent Progress

Knowledge of bulk compositions has been gleaned from remote sensing, determination of orbital dynamics, and samples of Earth, the Moon, and meteorites (including those from the Moon and Mars). Good progress has been made in determining the surface compositions of the Moon, of some asteroids, and, to some extent, of Mars and Mercury. In situ measurements for Venus, made at seven locations by (short-lived) landed Soviet missions, suggest basaltic and alkaline surfaces. However, the bulk composition remains poorly known. Synthesis of these results suggests that although some rock-forming elements occur in the inner solar system in chondritic relative proportions, the volatile elements are depleted.[1] Indeed, compositions of planetary basalt suites possibly reflect a gradient in the abundance of volatile elements, increasing with distance from the Sun.

Isotopic data on oxygen, hydrogen, and other volatiles provide clues to planetary compositions, their atmospheres, and early solar system processes and environments relevant to the origin of life. Isotopic data from Earth and Mars suggest that primary atmospheres were lost and later replaced by volcanic outgassing or addition from comets.[2] The (incomplete) measurements of the atmosphere of Venus are consistent with solar values and could reflect the influence of a primordial atmosphere, but the state of chemical and isotopic equilibrium of the surface and atmosphere is unknown. Each of the inner planets has a complex history of postaccretional processes that have contributed to and modified its surface and atmospheric compositions. Analysis of diverse surface materials, determination of their ages, and assessment of the processes that have affected them are needed in order to understand how volatile-element contents have evolved differently on each of the planets.

Future Directions

- *Mercury.* Basic information is needed on surface composition, internal structure, and distribution of mass, each of which provides important constraints on bulk major-element composition.
- *Venus.* Compositional measurements of the surface and the atmosphere (especially the noble gases) are needed in order to understand the bulk composition and the origin of Venus's atmosphere. Oxygen isotopic ratios would provide key geochemical constraints on the planet's composition for understanding differences among the inner planets and for testing models of formation. Measurements of the chemical state of the surface and near-surface environment are needed to understand surface and atmosphere interactions.
- *Moon.* Seismic data would resolve the internal structure, permitting a much-improved estimate of bulk composition. Samples of rocks from major unsampled terrains, primarily the South Pole-Aitken Basin, are needed to determine an accurate deep crustal composition and stratigraphy.

Important Questions

High-priority investigations relating to bulk compositions of the inner planets and their variation with distance from the Sun are as follows:

- Determine elemental and mineralogical surface compositions,
- Determine noble gas compositions of atmospheres,
- Determine oxygen isotopic compositions of the unaltered surface and atmosphere, and
- Determine interior (mantle) compositions.

Internal Structure and Evolution of the Core, Crust, and Mantle

Knowledge of the internal structure of the planets is fundamental to understanding their history after accretion. Key issues include dissipation of internal heat, core formation and associated issues concerning magnetic-field generation, distribution of heat-producing radioactive elements, and styles and extent of volcanism. Earth's crust is the product of differentiation and several billion years of recycling through plate tectonics, with water being a critical ingredient.

Mercury is small, and its ancient surface suggests a lack of crustal recycling or extensive resurfacing. Although models suggest that the silicate portion of Mercury differentiated to form a crust and mantle, little is known about its crust-mantle structure or composition. Similarly, recent results suggest that Mars probably has a mantle and core, but the interpretation is model-dependent. Based on analysis of lunar samples, the Moon began hot, with an ocean of magma some 400 km deep; its crust was extracted as the low-density component during solidification of the magma ocean, but insufficient heat remained to recycle material. Venus, on the other hand, has been geologically active within the past billion years, yet its surface is very different from Earth's and exhibits no similar plate tectonics. Processes of crustal formation and the dynamics of mantle movements are poorly constrained.

Recent Progress

Knowledge of the internal structure of the Moon is constrained by samples, limited on-surface geophysical measurements, and data from orbit. Results indicate a differentiated low-density, aluminosilicate crust of about 40 km to 100 km, overlying a ferromagnesian silicate upper mantle,[3,4] and a small iron-rich core.[5] Remote-sensing data show that the Moon has a strong hemispheric asymmetry. What caused the asymmetry is not known, but it is likely that it influenced the distribution and extent of subsequent volcanism. The topography of Mars also shows a dichotomy between the northern lowlands and the southern cratered highlands. Although several hypotheses have been posed to explain the dichotomy, including those related to both internal and external processes, these ideas remain untested.

Venus's topography is known from Pioneer Venus and Magellan measurements and, although these data reveal extensive tectonism and volcanism, the expressions of Earth-like plate tectonics are absent. Instead, topography and the relative youth of the Venusian surface indicate a major, possibly global, resurfacing that may have occurred episodically.[6,7] Although Venus appears to have an iron core, the absence of a magnetic field suggests that it does not have a magnetic dynamo, perhaps consistent with its slow rotation. Limited Mariner 10 data at Mercury indicate the presence of a magnetic field with a magnetosphere capable of standing off the solar wind most of the time. It is possible that a dynamo or a strong remnant magnetic field is present. Either way, Mercury's large metal core plays a key role. Whether Mercury and Venus have solid inner cores and liquid outer cores is not known.

Future Directions

Seismic data for each of the inner planets are ultimately needed to constrain the structure, mineralogy, and composition of the deep planetary interiors. Key investigations that address evolution of the crust, mantle, and core include the following:

- Determination of the horizontal and vertical variations in internal structures,
- Determination of the compositional variations and evolution of crusts and mantles,
- Determination of the major heat-loss mechanisms and resulting changes in tectonic and volcanic styles, and
- Determination of the major characteristics of iron-rich metallic cores (size and the nature of liquid and solid components).

The History and Role of Early Impacts

An early paradigm shift in the understanding of the solar system was the realization that impacts constitute a fundamental process, particularly in early planetary formation. For example, current understanding suggests that proto-Earth was struck by a Mars-size object, resulting in the formation of the Moon and setting Earth on a distinctive evolutionary path. Impact-generated heating likely caused partial to global melting of the terrestrial planets, leading to the formation of magma oceans and differentiation of the interior.

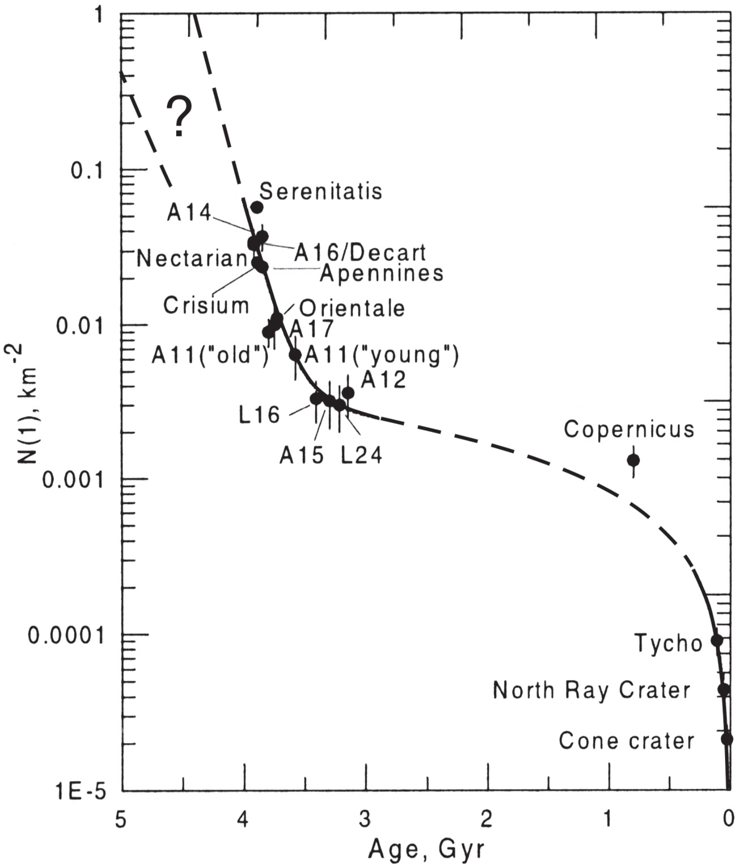

FIGURE 2.3 Cumulative crater frequencies (i.e., the number of craters equal to and larger than 1 km in diameter per square kilometer) with time, as derived from lunar surfaces dated from returned samples. Crater frequency data are then used to estimate the age of unknown planetary surfaces. The recent crater flux at 1 AU is partially constrained by terrestrial craters, but the period prior to 4.0 billion years is unknown. The apparent cluster of basin-forming events near 3.9 billion years is particularly puzzling and has several implications for early solar system history. Adapted from G. Neukum, B.A. Ivanov, and W.K. Hartmann, "Cratering Records in the Inner Solar System in Relation to the Lunar Reference System," *Space Science Reviews* 96: 55-86, 2001.

Large, early impacts played a key role in establishing the structure of the early crust, which remains exposed on the Moon, Mars, and the observed part of Mercury. This structure influenced subsequent surface and near-surface evolution, such as the emplacement of lunar lava flows. However, because data are incomplete, it is not known if global melting and differentiation occurred on all of the terrestrial planets, or if impact basins dominate the crustal structure of Mercury as they do on the Moon and to some extent on Mars. The history of volatiles and planetary atmospheres were also affected by impacts, both through implantation by comets and removal of gases through impact erosion.

The lunar impact record, dated by samples, is used to extrapolate surface ages throughout the solar system. However, there is considerable uncertainty in the early flux of impacts, with two models proposed. In one, the flux decayed exponentially with time; in the other, the flux peaked at about 4 billion years (Figure 2.3).[8] Because the lunar cratering record is used for dating events throughout the solar system, resolving the lunar cratering record is key.

Recent Progress

Only half of Mercury's surface has been seen and, while the Magellan mission provided global reconnaissance of Venus, it is not known if vestiges of early crust remain there. The paucity of impact craters on Venus suggests a relatively youthful surface. However, estimates of surface ages are poorly constrained, ranging from <250 million years to nearly a billion years old.[9] Samples from nine locations on the Moon enable dating of key events in lunar evolution, but the chronology of most large, early impactors is poorly known.

Future Directions

Understanding the role of early impacts requires age-dating key terrains on the Moon and Mercury, mapping all of Mercury, and obtaining compositional, mineralogical, and petrologic measurements of key terrains on the terrestrial planets. The following specific investigations need to be conducted:

- Determination of large-impactor flux in the early solar system and calibration of the lunar impact record,
- Determination of the global geology of the inner planets, and
- Investigation of how major impacts early in a planet's history can alter its evolution and orbital dynamics.

The History of Water and Other Volatiles and Evolution of the Inner Planets' Atmospheres

An accurate account of the history of water and other volatile compounds is essential for understanding the origins of the environments of the inner planets. Planetary atmospheres have been severely affected by processes that occurred after planetary formation, including internal processes (e.g., volcanism) and external processes (e.g., impact and late-stage accretion), but the data are insufficient to determine the exact evolutionary paths. Accurate measurements of hydrogen and isotopic abundances of noble gases and oxygen in the atmosphere, soil, and rocks are required. These data are necessary to determine the fraction of pristine, nebular volatiles versus later cometary-impact volatiles and to understand the loss rates of atmospheres in the early phases of planetary formation.

Recent Progress

The Moon and Mercury may have yet undetected significant species in their tenuous atmospheres.[10] At Mercury, coherent radar backscatter indicates volatiles at high latitudes.[11] Clementine data suggest buried water ice at the lunar south pole, while Lunar Prospector detected significant quantities of hydrogen at both poles, but the form, extent, and origin of such deposits are not known. Although volatiles are strongly depleted in the Moon's crust, the volatile content of the deep interior is poorly constrained. Mars also exhibits significant amounts of hydrogen in the polar regions. On the other hand, solar-wind implantation deposits hydrogen and helium in the lunar regolith. The principal volatile constituents of Venus and Mars are known.[12,13]

Much is known about the mechanisms of atmospheric loss—Jeans escape, hydrodynamic escape, exospheric sputtering, and solar-wind sweeping are the main processes. Application of these processes to Earth, Mars, and Venus is used to infer the past and present states of the atmospheres, particularly regarding the loss of water vapor.[14] For Mars and Venus, photochemical and other predictions of less abundant species exist, but no actual detections of them have been made.

Future Directions

Water and the volatile compounds that make up the atmospheres of the inner planets are also partitioned among the interiors, crusts, and hydrospheres of these planets. The evolution of water and volatiles since our solar system's formation is central to an understanding of terrestrial planets' evolution to either support life or prevent its inception. An exploration program that includes the following will achieve this new understanding:

- High-precision measurements of noble gases and light stable isotopes,
- Determination of the composition of magmatic volatiles, and
- Determination of the composition and source of the polar deposits on Mercury and the Moon.

WHAT COMMON DYNAMIC PROCESSES SHAPE EARTH-LIKE PLANETS?

The dynamical influences shaping Earth-like planets include the following:

- Processes that stabilize climate,
- Active internal processes that shape the atmosphere and surface environment, and
- Active external processes that shape the atmosphere and surface environment.

Recent progress in studies of each, likely future directions for research, and important questions that need to be addressed are outlined below.

Processes That Stabilize Climate

Venus, Earth, and Mars have complex interactions between the surface, atmosphere, and interior. Mars is most likely geologically quiescent, although because of variations in its motion around the Sun, it experiences changes in solar energy input and thus in cycles of water and carbon dioxide between polar caps, surface, and atmosphere. The connections between these environments on Mars and Venus are manifestly different from those on Earth. Looking and thinking beyond Earth's climate system will enable us to more deeply understand processes that affect climate and how they interact in establishing planetary environments. Understanding the factors influencing plate tectonics (initial planetary composition, internal dynamics, and the role of water) is of prime importance in understanding the stability of climate. The effects of clouds, volcanism, and tectonism on climate stability are also important but not well understood. Studies of the Moon and its formation are important to understanding how astronomical perturbations affect climate on terrestrial planets.

Recent Progress

Comparative studies of the surfaces, atmospheres, and interiors of the inner planets show that, while common physical processes operate on these planets, their interactions and collective effects are expressed differently.[15] On Earth, plate tectonics recycles crustal material and cools the interior. Carbon, oxygen, sulfur, and nitrogen cycle among the atmosphere, biosphere, oceans, crust, and interior. Earth's Moon helps stabilize obliquity and therefore seasonal variations.[16] Although Mars and Venus have their own, unique versions of volatile cycling, neither of them currently has plate tectonics or moons that affect their orbital stability.

Future Directions

Critical interactions between the interior and atmosphere of Venus are not understood. Science investigations central to understanding climate should do the following:

- Determine the general circulation and dynamics of the inner planet's atmospheres;
- Determine the composition of the atmospheres of the inner planets, especially trace gases and their isotopes;
- Determine how sunlight, thermal radiation, and clouds drive greenhouse effects; and
- Determine processes and rates of surface/atmosphere interaction.

Active Internal Processes That Shape the Atmosphere and Surface Environments

Processes taking place within a planet—including volcanic outgassing, generation of magnetic fields, and exchange or recycling between the surface, atmosphere, and interior—affect the current state of the surface and atmosphere. For example, prolonged volcanic eruptions can affect climate and atmospheric evolution. The magnetic field of a planet recycles ions back into the atmosphere and protects it from solar-wind erosion. Magnetic fields are generated by internal processes, most likely from an internal dynamo driven by differential rotation of a solid inner and liquid outer core. What would Earth currently be like without plate tectonics or without its protective magnetic field? The lack of plate tectonics on the other terrestrial planets, the lack of a magnetic field at Venus and the weak field at Mercury, and the remnant magnetization of Mars allow us to explore "alternative scenarios" for the current state of processes active on Earth and to understand the relative significance of the interplay between volcanic activity and atmospheric composition in generating and sustaining habitable environments.

Recent Progress

The hot interiors of planets drive tectonic and volcanic processes such as plate tectonics. Volcanic activity on the Moon and Mercury occurred early, activity on Mars extended longer, while Earth and probably Venus remain geologically active. On all of the inner planets, active internal processes contributed to their atmospheres through outgassing and, on most bodies, interactions continue between the surface and the atmosphere. Venus, the only other inner planet likely to still have a dynamic interior, lacks plate tectonics, and the evolution of its interior is a subject of much debate.[17] The rates of tectonic and volcanic activity are not quantified for Venus, and the ages of major surface units that would help constrain rates of volcanism cannot be determined from remotely sensed data.

Earth has a strong, dipolar magnetic field that stands off the solar wind. Mariner 10 data showed that Mercury has a dipolar field, aligned in the same sense as that of Earth and with 0.001 of its surface field strength.[18] Although the Moon has remnant crustal magnetism and anomalies, their source is not clearly understood. Recent results from the Mars Global Surveyor spacecraft indicate that Mars has remnant magnetism,[19] suggesting the possibility that a magnetic field once existed, enabling a thicker atmosphere.[20] Venus has no measurable magnetic field, although it is not known if one existed in the past.

On Earth, the lithosphere, hydrosphere, biosphere, and atmosphere participate in the cycling of volatiles such as water and carbon dioxide. The current lack of a hydrosphere and biosphere on Venus provides a unique opportunity to analyze the links between processes in the interior, volcanic activity, composition of the surface and atmosphere, generation and maintenance of the global cloud layer, and chemical weathering of the surface. Key steps include measuring the following: the composition of the lower atmosphere, isotopic noble gas abundances in the atmosphere, mineralogy and composition of surface rocks, and the rates of active processes on Venus by accurately dating key surfaces.

Future Directions

Knowledge of the current state of internal geologic activity as well as the state of evolution of the surface and of past or present magnetic fields is needed in order to characterize active processes on the inner planets. The highest-priority measurements are these:

- Characterize current volcanic and/or tectonic activity and outgassing;
- Determine absolute ages of surfaces; and
- Characterize magnetic fields and relationships to surface, atmosphere, and the interplanetary medium.

Active External Processes That Shape the Atmosphere and Surface Environments

The inner planets share a common environment in our solar system in which active processes such as solar-wind bombardment affect how the atmospheres and surfaces evolve. Because the inner planets are close to the Sun, a common loss process for their atmospheres is solar-wind sweeping, in which ionized species are removed from the top of exospheres by electric fields connected to the interplanetary medium. Magnetospheres can help recycle ions into the neutral atmosphere, but the efficiency of this process is unknown. Studies of the effects of the solar wind on planets with weak or no magnetic fields provide a basis for understanding how external processes affect atmospheric evolution.

Micrometeorite bombardment modifies the surfaces of Mercury and the Moon and injects material into their exospheres. Bombardment by larger objects is more infrequent, but it radically changes the surfaces and atmospheres over time. Cosmic rays, meteorites, ion bombardments, and implantation alter the structure of the uppermost regoliths of Mercury and the Moon. The same processes comminute, vaporize, and mix the regolith while adding exogenous material. These external processes affect each of the inner planets in different ways and at different scales, changing their surfaces and atmospheres in ways that determine how habitable environments are maintained.

Recent Progress

Pioneer Venus measured the radiation and particle environment for 14 years, resulting in our knowledge of the effects of external processes on the planet's upper atmosphere. The extent to which the lower atmosphere and surface are perturbed by external processes is not known but is thought to be minor because of the dense atmosphere. One exception could be deposition of volatiles by cometary impact. A better characterization of the escape rates of various species from the atmosphere of Venus will aid in an understanding of how that planet's atmosphere has evolved.

Mercury's dipolar magnetic field is believed to stand off the solar wind much of the time. The tenuous surface-bounded atmospheres of Mercury and the Moon are a result of meteoritic impact volatilization of both the surface and the impactor (sodium, potassium, and calcium) and solar-wind-implanted hydrogen and helium.[21] The origin of high-latitude trapped lunar and mercurian volatiles is currently a matter of intense discussion.

The combined effects of small-scale processes that mobilize and alter the surface on airless bodies have recently been recognized through detailed analysis of lunar soils enabled by improved instrumentation in Earth-based laboratories.[22,23] The nature and rate of such processes are still unknown.

Future Directions

Several investigations are important for understanding external processes active in the inner solar system. They should do the following:

- Make precise compositional measurements of the surface-bounded atmospheres of Mercury and the Moon and determine the relationship between ionospheres and magnetospheres,
- Quantify processes in the uppermost atmospheres of the terrestrial planets, and
- Quantify regolith processes on bodies with tenuous atmospheres.

WHAT FATE AWAITS EARTH'S ENVIRONMENT AND THOSE OF THE OTHER TERRESTRIAL PLANETS?

Discussion of the fate of Earth's environment and those of the other terrestrial planets is organized under the following headings:

- The vulnerability of Earth's environment as revealed by the diverse climates of the inner planets,
- The varied geological histories of the inner planets that enable predictions of volcanic and tectonic activity,
- The consequences of impacting particles and large objects, and
- The resources of the inner solar system.

Recent progress in studies relating to each of these factors, together with likely future directions for research, are outlined below.

Vulnerability of Earth's Environment As Revealed by the Diverse Climates of the Inner Planets

Mars is a small, frozen world, hostile to life because of its thin atmosphere and harsh radiation environment. Venus has a dense atmosphere that traps radiation so efficiently that its surface is as hot as an oven; the atmosphere is 10 percent of the mass of Earth's ocean and is a supercritical fluid at the surface. Given these two extremes and the awareness that humans are altering Earth's climate, what is the fate of Earth's environment? Can we inadvertently cause Earth to evolve to states similar to that of either Mars or Venus or some other inhospitable regime? To answer this question requires investigating the geochemical cycles that affect climate by determining the composition of the lower atmosphere and surface of Venus, how its atmosphere evolved to its present state, and how atmospheric loss processes affect bulk properties of the atmosphere and surface of terrestrial planets.

Recent Progress

Earth's climate record illustrates that there are wide swings in regional and globally averaged surface temperatures.[24,25] Mars once had liquid water on its surface, when the Sun's luminosity was less than it is today.[26] Evidence indicates that Venus's climate has varied significantly in the past billion years.[27] It is now known that terrestrial planetary environments are maintained by complex interactions among the surface, atmosphere, and interior. The physical states of the terrestrial planet environments have been the focus of exploration, including the photochemistry of Venus's clouds and the role of early volcanism on Mars. However, how these processes establish and maintain climate is poorly understood.

Future Directions

Global monitoring of Venus's atmosphere and climate; in situ elemental, mineralogical, and geochemical measurements of the planet's surface; and detailed data on the noble gas isotopes and trace gas abundances of the atmosphere are necessary in order to understand terrestrial planet climates. This should also include characterizing the geochemical cycles of sulfur, hydrogen, oxygen, nitrogen, and carbon. The most important investigation is the following:

- Characterize the greenhouse effect through meteorological observations.

Varied Geologic Histories That Enable Predictions of Volcanic and Tectonic Activity

Volcanism and tectonism reflect the release of heat from planetary interiors. These processes have operated throughout the history of Earth and will probably continue in the future. Manifested through volcanic activity and earthquakes, these processes have an enormous influence on society.

The inner planets all have indications of resurfacing by volcanism and crustal disruptions by tectonic processes. Although the timing and style of these processes vary among the planets, they provide clues to the evolution of planetary interiors and insight into possible future geologic activity. For example, volcanism on the Moon appears to span a wide range of time, but it decreased substantially in the last third of the Moon's history. In contrast, volcanic and tectonic activity on Venus has been extensive throughout its "visible" history, and the planet could be currently active. These two cases reflect (in part) the relative sizes of the bodies, in which internal activity extends over a length of time that scales with planetary diameter. Mercury's volcanic history is not known, although the impact record suggests an ancient surface, relatively unaffected by volcanism.

Although on Earth tectonism is manifested globally through plate motions, knowledge of the styles and history of tectonic deformation on all terrestrial planets is required in order to understand the general process and, thus, the behavior observed on Earth.

Recent Progress

Global mapping of Venus by the Magellan radar mission revealed a surface estimated to be less than 1 billion years old. The current explanation suggests that extensive "overturning" of the lithosphere resulted in near-global resurfacing. Although similar in size and composition to Earth, Venus does not appear to have plate tectonics. However, as on Earth, recent activity may be detectable in measurements in Venus's atmosphere and clouds through monitoring reactive volcanic gases (e.g., hydrogen chloride, hydrogen sulfide, and sulfur dioxide) or derived aerosols.

The Moon and Mercury have very different histories compared with those of Venus and Earth. The surface of Mercury has probably been modified by contraction associated with the cooling of its large iron core and possibly from stresses associated with the slowing of its spin rate over time, but the extent of volcanism is unknown.

Although it is not known when volcanism began on the Moon, evidence suggests that it was common prior to the last major basin-forming events (~3.8 billion years ago) and ceased much later, at about 2 billion years ago.[28]

Future Directions

A deeper understanding of how volcanism and tectonism vary over time and across planetary surfaces requires determining the current interior configurations and the evolution of the surface expressions of volcanism and tectonism. An understanding of the rates and chemistry of recent volcanism is necessary in order to make connections between geology and climate change. Specific recommendations are these:

- Assess the distribution and age of volcanism on the terrestrial planets, and
- Search for evidence of volcanic gases in inner-planet atmospheres.

Consequences of Impacting Particles and Large Objects

Collision between solar system bodies is a fundamental process, with enormous consequences for the formation, destruction, and sustainment of habitable environments. On Earth, the demise of the dinosaurs and other species exemplifies a process that has likely occurred numerous times on Earth. As currently understood, impact cratering was frequent following planetary accretion, and it declined sharply between 3 billion and 4 billion years ago. However, perturbations in the more recent impact flux and causes thereof and the identity of the impacting objects remain poorly known. In addition, a constant flux of interplanetary particles and ions impact the planets, interacting with their atmospheres and surfaces. Continuing to develop our understanding of the origins of the impactors and the factors affecting the flux should lead to a predictive capability and an improved understanding of links to human and other biological activities.

Recent Progress

The rates and history of impact cratering of the Earth-Moon system are understood through precise ages of lunar samples and documented impact craters on Earth. Since about 3 billion years ago, the average cratering rate on the Moon has been similar to that of Earth, and the rates are roughly consistent with those estimated from the present near-Earth flux of asteroids and comets.[29] Cratering rates, however, have probably not been constant, but have responded to fluctuations related to breakup of main belt asteroids, tidal disruption of comets passing close to

Jupiter, and perturbation of comets from the Oort cloud resulting from galactic tidal forces or gravitational pulses from passing stars or other concentrations of mass.

Future Directions

The continued discovery of craters in Earth's geologic record and future dating of materials on the inner planets will allow the definition of flux variations and the identification of impactors and causes of variability. The surfaces of Mercury and the Moon potentially provide the history of solar-wind activity in the inner solar system. In this case, the past holds the key to the future, and the past record is well preserved on the Moon and Mercury. Specific investigations should include the following efforts:

- Determine the recent cratering history and current flux of impactors in the inner solar system, and
- Evaluate the temporal storage and record of solar-wind gases.

Resources of the Inner Solar System

A basic component of planetary exploration is to characterize surface materials; in so doing, resources may be identified that have practical and economic use either in space or on Earth. In the absence of water and with the crustal recycling on Venus, Mercury, and Mars, ore resources may prove rare. Nonetheless, future exploration of these planets may reveal unexpected geological resources. In the near term, however, the only feasible resources of the inner planets are those of the Moon. Such resources are likely to play a prominent role in long-term exploration of the solar system by humans.

Recent Progress

Although the Moon is depleted of volatile elements, enrichments occur at the surface: (1) at the lunar poles, where hydrogen and perhaps other volatile species, possibly delivered by cometary or other volatile-rich impactors, have been trapped in cold, permanently shaded craters; and (2) in ordinary surface regolith, owing to implantation of solar wind.[30] The potential production of propellant is significant, because development costs for heavy lift launchers are high and have been viewed as stumbling blocks for planetary exploration strategies. The isotope ^{3}He is a potential clean fuel that is rare on Earth but is concentrated by the solar wind in lunar regolith.[31] Bulk construction materials are available, including metals such as iron and aluminum; ceramics; glasses; and sintered regolith, for a lunar variety of concrete, given a ready supply of water. Except for the polar deposits, most of the Moon's resources are well understood and await technology development for use.

Characterization of potential resources, especially confirmation of polar hydrogen deposits and determination of mineral/chemical form, is needed. Operation in the extreme cold of permanently shaded craters is a technical challenge that also needs to be addressed. Concentrations of materials may exist that some have argued are of economic interest, such as ^{3}He in lunar regolith. Such deposits may be identified through surface geochemical surveys and the analysis of samples of surface regolith and rocks. Geochemical indicators of ore processes may be subtle or minor; thus, sample return and analysis have the best likelihood of discovering such processes. In situ analyses, especially of the physical and geotechnical properties of the surface, are needed in order to proceed with mining and materials processing.

Future Directions

The next steps in determining which, if any, inner solar system materials may enable future human exploration activities include the following:

- Assess volatile resources, and
- Assess mineral resources.

INTERCONNECTIONS

Links to Astrobiology

Astrobiology is an integrating theme that provides a common thread for understanding planetary habitability and addresses some of the most exciting intellectual questions of our time, such as the nature of life and the existence of habitable worlds. Astrobiology not only includes the search for extant or extinct life, but also seeks to define the conditions that lead to habitable planetary environments and to discover whether the characteristics of our system that allow life to exist here are likely to be common or rare in the galaxy.

The terrestrial planets provide insights into the conditions that might have been favorable for organic evolution. A deeper understanding of the origin and evolution of volatiles, impact history, and their implications for composition and habitability is crucial. The astrobiology community recognizes the need for study of Venus in order to understand the implications of the differences between the evolutionary paths taken by Venus and Earth. Exploration of the inner planets must now include more detailed in situ experiments that characterize the mineralogy, geochemistry, and time-variable processes that occur on the surface. More detailed measurements of planetary atmospheres are needed in order to understand the general principles that drive climate. Most importantly, samples from the Moon, Mars, Venus, and Mercury must be returned to Earth's laboratories for exhaustive study. Only then will we approach an integrative understanding of the terrestrial planets so that we can answer the questions of what led to the uniqueness of our home world, what common dynamic processes shape Earth-like planets, and what the fate of terrestrial planetary atmospheres is.

Links with Mars

The program of exploration at Mars is motivated by the possibility that conditions favorable for life may have existed there in the past. Data from Mars missions are critical to address some of the questions for the inner planets outlined above. However, to understand the range of conditions that lead to habitable environments, measurements need to be made at Mercury, Venus, and the Moon that will maximize the science return from the Mars program.

The strategy for Mars exploration combines remote sensing, measurements made on the surface, and the return of samples to Earth from well-characterized localities on Mars. Because the cost of sample-return missions from Mars is high, emphasis has been on remote-sensing and landed missions that enable the identification of critical places from which the samples would be returned, consistent with the overall science objectives. At the same time, it is recognized that well-documented samples from nearly any site that is relatively well understood will provide an enormous advance in our understanding of Mars. The panel's strategy for the exploration of the other inner planets follows a similar path, leading to the return of samples to Earth. As outlined in the previous sections, samples afford the means to test specific hypotheses posed from orbital and lander missions. Most importantly, they provide data that cannot be otherwise obtained, such as radiometric ages for key surfaces and identification of isotopic and trace-element signatures of planetary formation and evolution processes.

Within the priorities set by NASA's Mars Exploration Program, not all aspects of Mars science will be completed in the core program. Thus, the Mars Scout Program, patterned on principal-investigator-led Discovery missions, is incorporated to provide flexibility in the exploration of Mars. Similarly, many aspects of the inner planets can be addressed by Discovery-class projects to respond to new findings, instruments, or approaches.

Links with Primitive Bodies

Small bodies (asteroids, comets, and Kuiper Belt objects) are considered to be remnants of the original "building blocks" of the solar system. The main belt of asteroids between Mars and Jupiter contains a range of small planetary bodies—some with diameters comparable to those of Pluto and Charon and some only meters across. Planetary accretion that continued elsewhere to form the inner planets was halted in this part of the solar system because of the growth of Jupiter.[32] Main belt asteroids thus appear to represent an early, but interrupted, state of planet formation.[33] Among the asteroids, several rocky bodies have achieved a size comparable to that of small planets; in at least one case (Vesta) early forms of internal processes common to the inner planets (such as differentiation and volcanism) had begun.[34,35] Many of the questions posed above are directly relevant to the large asteroids and argue for detailed exploration. Meteorite samples studied in Earth-based laboratories provide invaluable constraints on the composition of such primitive materials of the solar system. Yet not only is the link between meteorites and individual asteroids poorly known, but it is also clear that we do not have fully representative samples of the important building blocks. Systematic sampling of small bodies of the solar system is complementary to the high priority given to obtaining samples from each of the inner planets.

KEY TECHNOLOGIES, SUPPORTING RESEARCH, AND FACILITIES

Technology

In the next phase of exploration, access to the surfaces and atmospheres of the inner planets is required in order to address fundamental science questions. Without the development of enabling technologies, missions to the surfaces of planets with extreme environments, such as Venus and Mercury, are not possible. Enabling technologies are also necessary for sample-return missions to these bodies, which in turn are essential to answering some of the paradigm-altering questions described above. Enabling technologies include extreme temperature (hot and cold) survivability systems, sample transfer from surface to orbit, shallow drilling and sample handling capabilities, high-temperature balloon materials, long-lived and compact power sources, and surface and atmosphere mobility.

Contributing technologies for inner-planet missions help to reduce mission cost and increase capabilities. Contributing technologies include advanced in situ instrument technologies (including radiometric age-dating and chemical and mineralogical analysis), improved communication technologies, advanced propulsion, autonomous entry, descent and landing and hazard-avoidance software to reduce risk, and overall reductions in mass in order to maximize science return. For the Moon, a relay satellite would enable communications with and control of robotic assets (e.g., rovers and geophysical networks) on the farside.

Many of the enabling technologies can be developed and tested on Earth, while some require technology demonstration flights. The panel strongly advocates missions that both provide science results and validate technologies for future science missions.

Supporting Research and Analysis

A robust research and analysis (R&A) program is absolutely essential for maximizing the science return from missions to the inner planets. It is important that a broader range of research be conducted than is represented by the focused mission set implemented during the next decade. This integrated R&A approach should involve the full science community in harvesting the widest range of science return. A strong R&A program is necessary to stimulate science discussion and to lay a foundation for planning missions in subsequent decades. Laboratory spectroscopy, rock and soil experiments, tests in planetary environmental chambers, theoretical analyses, field studies, and detailed sample studies must occur in parallel with space missions. Many concepts and hypotheses associated with planetary exploration can be tested or evaluated using Earth-based laboratory or analog studies. Data gathered by each mission must be evaluated in the context of existing knowledge and integrated with other observations. Typically, the analysis of data from a specific mission extends years beyond the initial processing and release of data, and with each new data set, reevaluation of the older data sets is extremely important. Such studies require sustained and stable programmatic support to harvest and extend the scientific return on exploration missions.

Earth-Based Telescopes

Ground-based telescopes should be supported for robust planetary programs that deliver new discoveries (e.g., the Na, K, and Ca atmosphere at Mercury; SO_2 and other trace gases in Venus's atmosphere, and O_2 in

Mars's atmosphere) and supporting science (for example, association of Na and K with surface features at Mercury, studies of deep thermal emission and water vapor clouds, mineralogic mapping, and monitoring of seasonal and daily water vapor at Mars). Much of this work is done with small telescopes in the 1.5- to 4-m class, which are threatened in a period of building very large (8-m and greater) astronomical facilities for deep-sky exploration. In addition, the new airborne observatory SOFIA (Stratospheric Observatory for Infrared Astronomy) will be a significant resource for exploration of the inner solar system, especially for spectroscopy of Mercury and the Moon and isotopic studies of the atmospheres of Venus and Mars. These facilities should be kept available for synoptic monitoring of inner-planet atmospheres (e.g., SO_2 and other molecular species at Venus, water at Mars, and Na and K at Mercury and the Moon). The planetary radar facility at Arecibo observatory should also be available for inner-planet studies, especially for Mercury.

Sample Curation and Laboratory Facilities

An integral part of the exploration of the inner planets includes the return of multiple samples from key planetary terrains, as well as atmospheric samples from Venus. The return of samples requires detailed planning and the implementation of appropriate facilities and protocols to receive the samples, enable initial analysis, and distribute the samples to the scientific community, all consistent with issues such as planetary protection. Such samples will most likely be very small and unique, thus requiring the development of specialized equipment and procedures. Although some of this infrastructure will be in place through the Mars Exploration Program, provisions must be made to accommodate the full spectrum of potential materials returned from the inner planets.

RECOMMENDATIONS OF THE INNER PLANETS PANEL TO THE STEERING GROUP

Detailed exploration of the inner planets is crucial for developing the necessary understanding about the uniqueness of the planet on which we live and the knowledge that can affect the future of this planet. Much highly significant science can and should be accomplished in the next decade.

After a careful evaluation of numerous near-term mission options for the inner planets, two missions stand out as providing the most abundant and highest-priority science. Both are medium-class missions. Although large missions to the inner planets are feasible and would certainly be of enormous value, the Inner Planets Panel thinks that the timing of these two priority missions and the investment made would be well tuned to the current economic and political climate. Table 2.1 summarizes how these missions address key science questions discussed above. The panel also provides a prioritized list of science goals and objectives for small missions or missions of opportunity.

Mission Priorities

The Inner Planets Panel's highest-ranked science missions are as follows:

1. *Mercury Science.* The successful implementation of the Messenger mission to Mercury, designed for the basic reconnaissance of Mercury's geology, atmosphere, magnetosphere, and topography, will finally complete our basic knowledge of the planets in the inner solar system. This is a long-standing high priority for exploration, and the panel reaffirms the strong community consensus for support. The panel explicitly reiterates the essential nature of the science objectives as being carried out by Messenger and expects full replacement in the event of unforeseen implementation problems.

2. *Venus In Situ Explorer (VISE).* The VISE mission is the highest-ranked new exploration mission for the inner planets. It is a detailed exploration and study of the composition of Venus's atmosphere and surface. Venus and Earth possibly had very similar surface conditions early in their histories, but Venus's subsequent evolution differed radically from that of Earth, developing an environment unsuitable for life. However, Venus is still a dynamic world with active geochemical cycles and nonequilibrium environments in the clouds and near surface that are not understood. VISE will make compositional and isotopic measurements of the atmosphere on descent

and of the surface on arrival at Venus. A core sample will be obtained at the surface and lofted to altitude, where further geochemical and mineralogical analyses will be made. In situ measurements of winds and radiometry will be obtained during descent, ascent, and at the balloon station. Scientific data obtained by this mission would help to constrain the history and stability of the Venus greenhouse and the recent geologic history, including resurfacing. The technology development achieved for this mission will pave the way for a potentially paradigm-altering sample-return mission in the following decade.

3. *South Pole-Aitken Basin Sample Return (SPA-SR).* The next highly ranked mission for inner solar system exploration is understanding basin-forming processes and impact chronology by returning samples from the South Pole-Aitken Basin on the farside of the Moon. The Moon provides a baseline for much of planetary science, and science questions associated with the Moon are at a high level of maturity. The South Pole-Aitken Basin is the largest known basin in the solar system and the oldest and deepest impact structure well preserved on the Moon (Figure 2.4). This giant basin allows access to materials from the interior of a small, differentiated planet. The SPA-SR mission will obtain samples of materials produced during this enormous impact event, enabling analysis

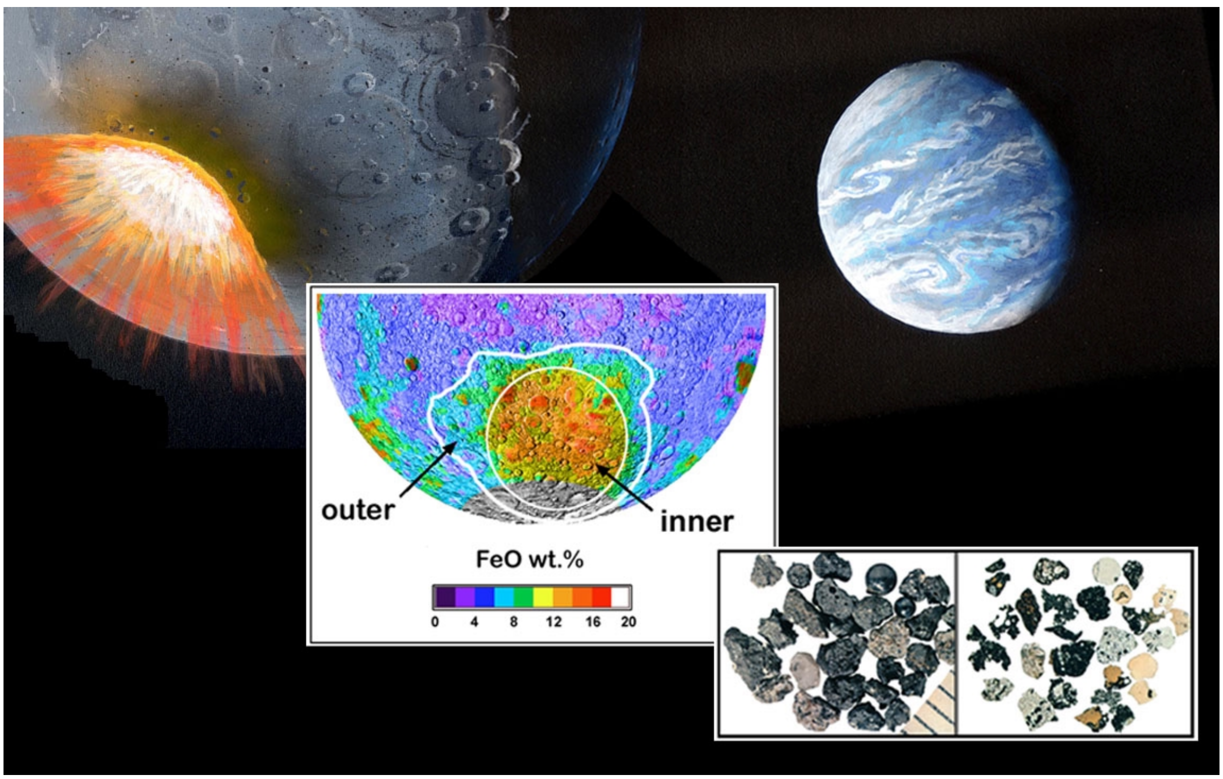

FIGURE 2.4 The Moon's South Pole-Aitken Basin at the moment of formation. A multi-ring basin formed as the initial cavity expanded and rim structures slumped into the growing depression. The SPA impact is expected to have excavated through the crust and into the upper mantle. The current basin interior remains distinctly FeO-rich, as determined from Clementine multispectral data (*middle image*). Lunar soils typically contain the diversity of representative rock types (*lower right*): note the millimeter scale. The date of SPA formation is not known, but early Earth was probably closer to the Moon than it is now, and may have been rotating faster (producing such cloud bands). Painting by W.K. Hartmann, 2002. Figures adapted from B.L. Jolliff, J.J. Gillis, L.A. Haskin, R.L. Korotev, and M.A. Wieczorek, "Major Lunar Crustal Terranes: Surface Expression and Crust-Mantle Origins," *Journal of Geophysical Research* 105: 4197-4216, 2000, and J.A. Wood, J.S. Dickey, U.B. Marvin, and B.N. Powell, "Lunar Anorthosites and a Geophysical Model of the Moon," in A.A. Levinson (ed.), *Proceedings of the Apollo 11 Lunar Science Conference Vol. 1*, Pergamon Press, New York, 1970, pp. 965-988.

TABLE 2.1 Summary of Priority Science Investigations Addressed by the Inner Planets Panel's Highest-Ranked Inner-Planet Missions

			Under Way	Near-term		Long-term	
Theme	Questions	Priority Science Investigations	**Mercury Messenger**	Venus In Situ Explorer	Moon SPA-SR[a]	**Venus Sample Return**	**Geophysical Network Science**
Past: What led to the unique character of our home planet?	a. What are the bulk compositions of the inner planets and how do they vary with distance from the Sun?	1. Determine elemental and mineralogic surface compositions.	xxx	xxx	xxx	xxx	
		2. Measure noble gas composition of atmospheres.		xxx		xxx	
		3. Measure oxygen isotopic ratios of the unaltered surface and atmosphere.			x	xxx	
		4. Determine interior (mantle) compositions.			xxx	xxx	xx
	b. What is the internal structure and how did the core, crust, and mantle of each planet evolve?	1. Determine horizontal and vertical variations in internal structures.	xxx		x		xxx
		2. Determine compositional variations and evolution of crusts and mantles.	xx	x	xxx	xxx	xx
		3. Determine major heat-loss mechanisms and resulting changes in tectonic and volcanic styles.	xxx	x	xx	xx	xx
		4. Determine characteristics of Fe-rich metallic cores (size; liquid and solid components).	xx			xx	xxx
	c. What were the history and role of early impacts?	1. Determine large-impactor flux in the early solar system and calibrate the lunar impact record.			xxx	xxx	
		2. Determine the global geology of the inner planets.	xxx	xx	xx	xx	xx
		3. Investigate how major impacts early in a planet's history can alter its evolution and orbital dynamics.	xx		xxx		xx
	d. What is the history of water and other volatiles and how did the atmospheres of inner planets evolve?	1. Make high-precision measurements of noble gases and light stable isotopes.		xxx		xxx	
		2. Determine the composition of magmatic volatiles.		x	x	xxx	
		3. Determine the composition and source of the polar deposits on Mercury and the Moon.	xx				
Present: What common dynamic processes shape Earth-like planets?	a. What processes stabilize climate?	1. Determine the general circulation and dynamics of the inner planets' atmospheres.		xx		xx	xxx
		2. Determine the composition of the atmospheres, especially trace gases and their isotopes.		xxx		xxx	
		3. Determine how sunlight, thermal radiation, and clouds drive greenhouse effects.		xx		x	xxx
		4. Determine processes and rates of surface/atmosphere interaction.		xxx		xxx	xx

	b. How do active internal processes shape the atmosphere and surface environments?	1. Characterize current volcanic and/or tectonic activity and outgassing.		xx			xxx
		2. Determine absolute ages of surfaces.			xx	xxx	
		3. Characterize magnetic fields and relationships to surface, atmosphere, and the interplanetary medium.	xxx				xx
	c. How do active external processes shape the atmosphere and surface environment?	1. Make precise compositional measurements of the surface-bounded atmospheres of Mercury and the Moon and determine the relationship between ionospheres and magnetospheres.	xxx				
		2. Quantify processes in the uppermost atmospheres of the terrestrial planets.	xxx	x			
		3. Quantify regolith processes on bodies with tenuous atmospheres.	x		x		
Future: What fate awaits Earth's environment and those of the other terrestrial planets?	a. What do the diverse climates of the inner planets reveal about the vulnerability of Earth's environment?	1. Characterize the greenhouse effect through meteorological observations.		xx		xx	xx
	b. How do varied geologic histories enable predictions of volcanic and tectonic activity?	1. Assess the distribution and age of volcanism on the terrestrial planets.	xx	x	x	xx	x
		2. Search for evidence of volcanic gases in inner planet atmospheres.		xxx		xxx	
	c. What are the consequences of impacting particles and large objects?	1. Determine the recent cratering history and current flux of impactors in the inner solar system.	xx		x	xx	xx
		2. Evaluate the temporal storage and record of solar-wind gases.		xx		xx	xx
	d. What are the resources of the inner solar system?	1. Assess volatile resources.	xx	xx		xx	x
		2. Assess mineral resources.	xx	xx	xx	xx	x

NOTE: The expected science returns from each of the missions shown are as follows: xxx = highly significant, xx = very useful, and x = supporting. Missions listed in boldface either are under way or are part of long-term planning.

[a]South Pole-Aitken Basin Sample Return mission.

of the effects of early, large impacts on the structure and evolution of the planets. Returned samples will include both soil and diverse rock chips.

Medium-Class Missions

Venus In Situ Explorer

The Inner Planets Panel's highest-ranked new mission for the next decade is the Venus In Situ Explorer (VISE). It would provide key measurements of the atmosphere and surface, as well as test technologies needed for a Venus surface and atmospheric sample-return mission in the subsequent decade.

Science measurement objectives of VISE are as follows:

- Determine the composition of Venus's atmosphere, including trace gas species and light stable isotopes;
- Accurately measure noble gas isotopic abundance in the atmosphere;
- Provide descent, surface, and ascent meteorological data;
- Measure zonal cloud-level winds over several Earth days;
- Obtain near-infrared descent images of the surface from 10-km altitude to the surface;
- Accurately measure elemental abundances and mineralogy of a core from the surface; and
- Evaluate the texture of surface materials to constrain weathering environment.

A Venus atmospheric and surface sample-return mission has been identified as the step in inner-planets exploration that is absolutely essential for determining why Venus has evolved such a different environment from that of Earth. This mission is complementary to the Mars surface sample-return mission, utilizing some common elements, such as an ascent capability and orbital rendezvous. However, several elements are unique to returning a sample from Venus and need to be demonstrated in situ. Development of these technologies will enable future sample-return and potential Discovery-class missions to Venus.

The key elements that will be tested by the Venus In Situ Explorer mission include the following:

- Aeroshell entry into Venus's atmosphere;
- Passive insulation and survival in the extreme environment of Venus;
- Sample acquisition and handling—a surface drill to obtain a sample quickly—for example, in less than 1 hour; and
- An ascent package that would loft the sample by balloon to an altitude of 70 km and survive for several Earth days.

Atmospheric Science Objectives. The composition of the lower atmosphere of Venus is unknown. Without this knowledge, comparisons of the factors that affect climate on Earth and on Venus, including photochemistry, clouds, volcanism, surface-atmosphere interactions, and the loss of light gases to space, are impossible. VISE will measure the abundance of trace gas species in the lower atmosphere of Venus to parts per million accuracy, enabling an understanding of how these processes affect terrestrial planetary climates. A fundamental quest is to understand how and why Venus, roughly the same size, composition, and distance from the Sun as Earth, has evolved to such a different state. The record of planetary atmospheres is contained in the isotope ratios of the most inert gases—xenon, krypton, argon, and neon. Are planetary atmospheres the remnants of gases that were originally solar in composition but then suffered massive hydrodynamic escape,[36] or did they acquire atmospheres from volatiles that had already been differentiated?[37] What was the role of impacts on the ultimate compositions and evolution of the terrestrial planets? Discrimination between these events for each of the inner planets is possible if noble gas isotopic ratios can be measured with a state-of-the-art neutral mass spectrometer. Previous spacecraft measurements have been inadequate to address these issues. VISE will determine the noble gas abundances and isotope ratios to sufficient accuracy to distinguish between hypotheses of the origin and evolution of Venus's atmosphere. A meteorological package will measure atmospheric pressure and temperature profiles down to the surface, and pressure, temperature, and winds at the surface. Cloud-level winds will be determined by tracking the ascent balloon during its 3.5-day lifetime, providing improved data on atmospheric dynamics and the origin of Venus's mysterious atmospheric superrotation.

Surface Science Objectives. The former Soviet Union's Venera landers returned basic elemental chemistry and images of four sites on the surface,[38-40] and Magellan data provided evidence of possible evolved volcanic deposits.[41] However, we lack sufficient information on surface elemental abundances and mineralogy to determine the degree of crustal evolution on Venus. The VISE mission would measure elemental compositions at a surface site complementary to those of the Veneras. Mineralogy of a surface sample core will be obtained for the first time, allowing analysis of any weathered layer and testing for depth of alteration and occurrence of unaltered material. Textural analysis of the sample using a microscope imaging system would provide information on the formation and nature of surface rocks. These data will be used to constrain questions outlined above. Despite global radar coverage of Venus by Magellan, little is known of the surface morphology at scales of 1 to 10 m. Without such information, it is difficult to determine how the plains formed and to understand the nature of mobile materials on the surface. A descent camera on the lander will provide the first broadscale visible images of the surface, with images returned from about 10 km altitude to the surface. These images will enhance interpretation of the Magellan radar images by providing ground-truth data on the surface texture of the lava flows that make up Venus's plains. The morphology and texture of these flows can be related to emplacement rate, volatile content, and rheology, which are needed in order to understand the role of volcanism in shaping the atmosphere and surface of Venus. Images of Venus's surface will also be returned from the lander, with filters chosen to provide compositional information. These images will help to determine the recent geologic history of Venus and will resolve differences in the interpretation of Venus's resurfacing history.[42]

Implementation. Science measurements will be made during three VISE mission phases: (1) the descent phase, with atmospheric experiments and descent imaging; (2) the landed phase, with surface imaging and atmospheric and surface chemistry; and (3) the ascent phase, with surface mineralogy and atmospheric circulation analysis. The panel stresses that VISE needs to be kept simple, with limited but focused objectives. The panel assumes that the instrument portion of the mission will be competed either as a package or individually.

Deep-atmosphere measurements should include these:

- A neutral mass spectrometer with an enrichment cell,
- A meteorological package that includes pressure and temperature sensors and wind-speed measurements at the surface, and
- Radio science investigations that track the ascent balloon, measuring cloud-level zonal winds.

Surface science experiments should include these:

- Near-infrared descent and lander cameras, with filters chosen to maximize surface-composition information;
- An instrument to measure the elemental geochemistry of a surface sample, likely an x-ray fluorescence analyzer or a new instrument utilizing technologies that are currently being developed. This measurement will be done inside the lander on the surface;
- An imaging microscope to analyze the core sample during ascent;
- An instrument to measure surface mineralogy. As this measurement requires time and benign conditions, it will occur at high altitude inside the ascent package; and
- Auxiliary experiments, such as a surface seismometer could be included, if mass margins and cost permit.

South Pole-Aitken Basin Sample Return

The return to Earth of rock fragments from the largest impact structure on the Moon, the South Pole-Aitken Basin, will address fundamental questions of inner solar system impact processes and chronology. Because these materials sample the deep interior, they would greatly increase our knowledge of the differentiation of planetary bodies and of the structure and composition of the Moon. Key measurements to be made on returned samples include radiometric ages of impact-melt rocks from the South Pole-Aitken Basin-forming event, and chemical, isotopic, and petrologic investigations of igneous and volcanic rocks from the deep crust and upper mantle of the Moon. This mission is considered a medium-class mission.

The SPA-SR mission will address fundamental issues relevant to the impact history of the inner planets and the Earth-Moon system and key remaining issues of lunar science. During Apollo, we sought to understand how a small planet sorts itself out—or differentiates—after its formation. What the Apollo and Luna missions—which investigated a limited region of the Moon's nearside—found was a considerably more complex planetary body than expected, and we have not really answered the question adequately. Remote-sensing results have recently provided the global context to address this issue as well as the effects of giant impacts in the early solar system.

Most models for the early evolution of the Moon include initial lunar differentiation forming segregated layers that are negatively buoyant and become gravitationally unstable, sinking toward the interior of the planet. Many aspects of the subsequent history, such as core formation and the generation of mare basalts, are linked to these events. Similar models have been proposed for Mars and Venus, and thus the characterization of the lower crust and upper mantle of the Moon will not only be a very significant step in distinguishing among several models for early lunar evolution, but it also will provide insight into processes that are likely to have occurred on other planets.

Solar System Science Objectives. The South Pole-Aitken Basin is the largest known structure of its type in the solar system and the oldest well-preserved basin on the Moon. Its age provides a key constraint on understanding basin-forming impact chronology throughout the solar system. Samples of materials produced by this enormous impact event will help decipher the following:

- Effects and timing of early, large impacts on planetary structure, differentiation, and orbital dynamics;
- The depth to which the impact penetrated (from sample composition and mineralogy); and
- The composition and origin of the impacting object (through trace-element and isotopic analyses).

Inner Solar System and Earth-Moon System Science Questions. Radiometric dating of samples of impact melt from the South Pole-Aitken Basin (and possibly from nearby smaller but later basins) will provide key evidence regarding the inner solar system and Earth-Moon system cratering chronology. The age of the South Pole-Aitken Basin will constrain the period of late, heavy bombardment and will provide a critical test of the hypothesis that the heavy bombardment was punctuated by a cataclysm, or spike, in the flux of large impactors. Understanding the bombardment flux is especially relevant for the Earth-Moon system and the evolution of early terrestrial environments.

Lunar Science Pivotal and Foundational Questions. The farside South Pole-Aitken Basin represents the principal major lunar terrain that remains unsampled.[43] Despite numerous subsequent smaller impacts, the enormous South Pole-Aitken Basin retains its distinct regional geochemical anomaly, observed remotely in FeO and thorium concentrations.[44,45] Recent remotely sensed information further suggests that the floor of the basin may largely represent the mineralogy of the Moon's lower crust, although impact breccias could contain mantle rocks as clasts (and mantle rocks may be distributed within the regolith).[46-48] Analysis of materials from the basin thus is expected to provide key information regarding fundamental problems of the present-day surface of the Moon and its geologic history, including the following:

- Composition and mineralogy of the lower crust determined directly from samples, allowing testing of models for the differentiation of the Moon's crust and mantle;
- Composition and mineralogy of the mantle (potential rocks or clasts in breccia would be the first direct samples of the lunar mantle);
- Ancient materials from the lunar farside that are not biased by the nearside impact basins, which dominate current Apollo and Luna samples;

• Validation of compositional remote sensing over a major region of the Moon for which no representative samples are known to exist in Apollo, Luna, or meteorite collections, and where existing data are ambiguous or otherwise not well understood (enabling improved determination of bulk composition);

• Sources of observed anomalous concentrations of thorium and other heat-producing elements to understand lunar differentiation and thermal evolution, including volcanism. This also addresses the origin of global planetary asymmetry and whether Th is enriched in the Moon relative to Earth, which is important for understanding the origin of the Moon from an early giant impact into the Earth; and

• Ages and compositions of farside basalts to determine how mantle source regions on the farside of the Moon differ from regions sampled by Apollo and Luna basalts.

From experience with Apollo regolith samples and because of the efficiency of lateral and vertical mixing, a diversity of rock samples is expected in a representative sample from well-selected sites within SPA.

Implementation. The SPA-SR mission concept includes a robotic lander with automated scooping and sieving capability to enhance the return of rock fragments along with bulk regolith. A kilogram of returned mature lunar soil without sieving would be expected to include some 5,000 rock fragments in the 1- to 10-mm range. To maximize the likelihood of obtaining a sample of original SPA basin impact-melt rocks and other desired materials, a roving capability or a multiple (three) lander concept could be employed. If multiple landers were incorporated, important lunar geophysical network science could be obtained to provide a structural context for the basin and the returned samples. The mission would include descent imaging to provide geologic context. A relay satellite is also required for command and control and to enable extended network science. This mission would serve as a testbed for key technology development associated with automated sampling, encapsulation, and return to Earth.

Discovery and Small-Class Missions

Summarized below are science objectives that could likely be met within or below the Discovery cost caps for the inner planets. These relate to objectives that can be achieved within the R&A program (Earth-based facilities), as missions of opportunity, or in collaboration with foreign investigations, or as peer-reviewed Discovery missions. The panel provides a list of such prioritized objectives for Mercury, Venus, and the Moon.

Mercury Science

The following investigations can be addressed by Earth-orbiting and/or ground-based telescopes or by Discovery missions that are complementary to Messenger:

• Investigate high-latitude volatiles to verify deposits (composition, extent, depth), to determine sources (solar wind, cometary, meteoritic) and history (recent versus ancient), and to understand the deposition process.

• Acquire a complete mineralogical map of the surface to understand variations among the terrestrial planets in crustal formation and surface evolution.

• Analyze the morphology and stability of the magnetosphere by measuring the intensity and distribution of ionic species emissions from beyond Mercury's orbit. This provides an opportunity to observe active space weather before it reaches Earth.

• Study the morphology of the neutral atmospheric species to determine if they are provided from surface materials, the interplanetary medium, meteoritic flux, endogenic sources, or a combination of these.

Significant technological advances or innovative approaches will be necessary in order for the following objectives to fit within an augmented Discovery-class mission:

• Return a sample from the surface to place Mercury in the context of solar system chemistry, determine volcanic and thermal history, and calibrate the crater flux (age dating).

- Emplace a geophysical network (seismic, heat flow) to determine internal structure, distribution of heat-producing elements, lateral and vertical heterogeneity of crust and mantle, and the true density of the core. Geophysical network science would address how small bodies differentiate and how the bulk composition of Mercury is related to the composition of the terrestrial planets.

Venus Science

Some of the following objectives can be addressed, either alone or combined with others, by new Discovery missions; some will be addressed by missions of the European Space Agency (ESA) and Japan's Institute of Space and Astronautical Science (ISAS); and others can be addressed by ground- or space-based observing programs.

- Lower-atmosphere trace gases and dynamics. Information is needed on how trace species vary over time and space and how they participate in cloud-forming processes, thermochemical reactions, and reactions with surface minerals. Such observations (e.g., by an advanced infrared imaging spectrometer) can also be used to look for direct evidence of extant volcanism.
- Monitoring global geological processes, such as volcanism, tectonics, and mass wasting, by imagery and topography with horizontal resolution in the few tens-of-meters range. Techniques are available for detecting changes on planetary surfaces (e.g., inflation of active volcanoes before eruptions) on centimeter scales.
- Exospheric mass loss and thermospheric dynamics. A suite of instruments can operate from Venus orbit or from HST and JWST to measure the loss of light species from Venus's atmosphere (this is key to understanding how Venus evolved to a state so different from that of Earth).
- Geothermal heat flow measured at multiple locations to determine rates of heat flow within the planet and between the surface and atmosphere and to lead to better understanding of volcanism and tectonics of the crust and mantle. (This objective will likely require significant technology development.)
- Measurement of middle-atmosphere trace gases and dynamics (by submillimeter heterodyne technology and direct Doppler wind measurements).

The following objectives may be moved into the Discovery class with technologies developed for VISE:

- Visual reconnaissance of the surface below the clouds to provide important ground-truth for Magellan radar images and far more refined geological interpretation of the surface;
- Global atmospheric dynamics explored in detail with long-lived instruments (e.g., on a fleet of balloons), including in situ pressure and temperature measurements, and possibly also direct measurements of solar and thermal radiation;
- Noble-gas and trace species measurements made with a simple Venus atmosphere sample-return mission. Such measurements are essential for understanding the origin and evolution of Venus's atmosphere (and for comparisons with Earth). Analyses on Earth would then be performed that would allow the measurement of noble and trace gas species to many orders higher precision than has been done for any planet other than Earth.

Lunar Science

New Discovery-class missions can address most of the following objectives wholly or in part. Several are planned to be addressed by European and Japanese lunar missions that are scheduled for launch within the next 5 years and will provide valuable opportunities for U.S. participation.

- Geophysical network science (seismic, heat flow) to determine internal structure, distribution of heat-producing elements, lateral and vertical heterogeneity of crust and mantle, and the possible existence of an iron-rich core. Geophysical network science would address how small planetary bodies differentiate, how the bulk composition of the Moon is related to the composition of Earth, and how planetary compositions are related to nebular condensation and planetary accretion processes (the Japanese Lunar-A mission contains two such instrumented penetrators);

- Investigation of the extended history of basaltic volcanism and calibration of the impact flux by returning a sample from the youngest lunar lavas (e.g., Lichtenberg-Rümker Hills). This would also address why basalts formed where they did in space and time (e.g., nearside-farside dichotomy and origin/evolution of the Procellarum region), and how the Moon cooled generally;
- Investigation of polar volatiles to verify deposits (character, mineralogy, composition, extent, depth), to determine sources (solar wind, cometary, meteorite) and history (recent versus ancient), and to understand processes of volatile migration and deposition on airless bodies;
- Determination of topography at high resolution (hundreds of meters to kilometers), as done by the Mars Orbiter Laser Altimeter (MOLA) on Mars Global Surveyor, in order to carry out detailed geologic investigations as well as to address the geophysical properties of the Moon's crust and mantle and the Moon's thermal evolution from hot and weak to cold and rigid;
- Determination and mapping of the mineral composition of the surface (through hyperspectral imaging) at sufficient spatial resolution to advance understanding of the petrologic relationships within and the origins of principal geologic units;
- Targeted area studies to understand impact chronology, especially the post-3 Gyr flux history and spikes or other periodicity in the impact flux (accomplished by age-dating key stratigraphic units and impact-crater melt rocks with returned samples);
- Determining the major-element composition of the surface of the Moon (including magnesium, aluminum, and calcium and other measurable elements at improved resolution compared with existing data) in order to better characterize the distribution of materials on the lunar surface and to understand the formation, differentiation, and bulk composition of the Moon;
- Stereo imaging coverage for high-resolution (e.g., 10 m), three-dimensional definition of geology and surface morphology to address local and regional issues (geologic interpretation, resource evaluation, Moon-base planning); and
- Geological site characterization in order to derive the geological evolution of the surface at key locations and to deconvolve the interplay between tectonic, impact, and volcanic processes (e.g., extended/long-duration rover traverse, imaging, and in situ analysis).

A Long-Term Exploration Strategy for the Inner Planets

The inner solar system affords the opportunity to address broad objectives for understanding the history, current state, and potential future of habitable planets. The Inner Planets Panel's strategy is to focus on the highest-priority science objectives for Mercury, Venus, and the Moon in the decade 2003-2013. Exploration efforts in the subsequent decade should focus on the return of samples from Venus and Mercury and on essential network science. The latter involves the establishment of multiple surface stations operating concurrently on a planet, and are referred to as "Geophysical Network Science" in Table 2.1. Missions to implement these networks would involve individual projects for Mercury, Venus, and the Moon. Because of the challenges posed by network science and, in particular, sample-return missions, it is critical that key technologies be developed and proven in order to enable their implementation. Thus, a second-order aspect of the Venus In Situ Explorer mission includes developing technologies for obtaining samples and lifting them from the surface. This technology will draw on heritage currently being established for the Mars sample-return program. It should be noted that a Venus sample-return mission, perhaps the highest-priority mission for inner planet exploration in the subsequent decade, is the only way to accomplish the following:

- Measure the isotopic composition of oxygen, to provide crucial information on this important characteristic of solar system formational processes;
- Obtain the isotopic composition of certain elements (e.g., Nd, W, Hf, Sr, Pb, Os, for which specific isotopes are products of radiogenic decay), to address the timing and extent of metallic core formation, the timing

and extent of mantle differentiation, and the depth, mineralogy, and chemical composition of source regions for these basalts; and

- Determine the age of returned rocks, to constrain the geologic history of Venus and allow comparison with the Earth.

Not all of the fundamental science issues for the inner planets can be addressed by the priority missions proposed here. However, as discussed earlier, substantial advances must be made in understanding how planets work, and much can be achieved through one or more focused Discovery-class missions. In addition, an integral part of the exploration of the inner planets is the integration of data analysis, supporting research, technology development, and education and public outreach programs with flight projects. For example, establishment of sample receiving facilities and the laboratories for the analysis of extraterrestrial materials must be in place well before the return of samples. Although such capabilities are likely to be implemented within the context of the Mars Exploration Program, plans must accommodate non-martian materials. Similarly, R&A supporting facilities and studies of planetary processes (e.g., laboratory, field-analog, computer modeling) must be supported sufficiently to enable both planning and scientific validation of results from flight projects. Most importantly, robust data analysis programs are essential to harvest the investment made with flight programs. Ground-based observations are expected to continue to make major contributions to monitoring atmospheric changes and mapping.

In conclusion, the inner planets hold fundamental clues to the development of Earth-like planets in our solar system and elsewhere. They provide valuable insights into the paths toward and stability of habitable environments. The most fundamental questions about these planets, such as their nature, their compositions, the interactions of their surfaces and atmospheres, and the role of impacting objects, will be addressed by the missions recommended here.

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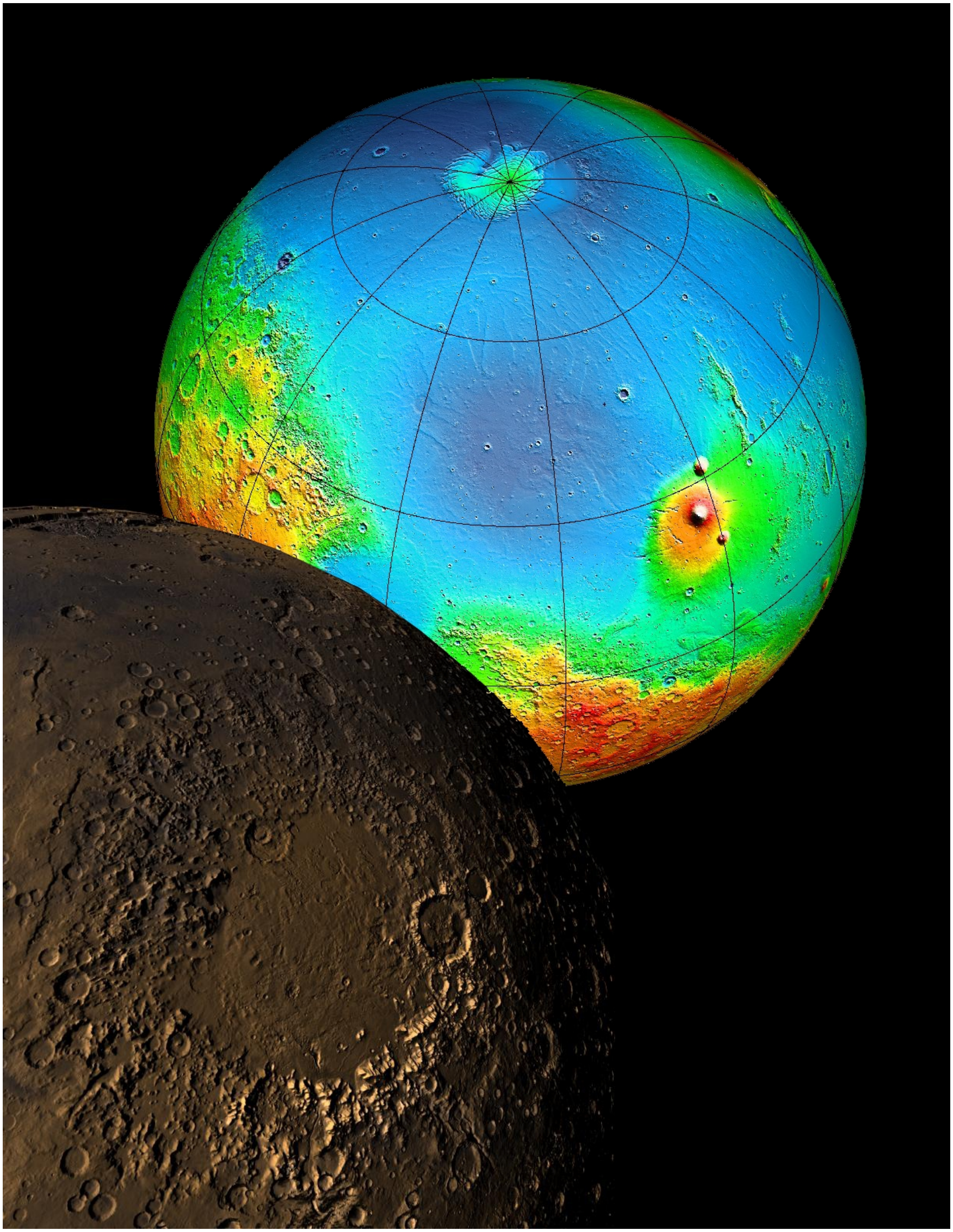

3

Mars: The Evolution of an Earth-like Planet

The first high-resolution images acquired of Mars by the Mariner 4 spacecraft at the dawn of the space age shattered popular notions of Mars. Far from being an oasis, the surface of Mars appeared to be as battered and barren as the Moon. With its thin atmosphere and bitter cold temperatures, Mars was more parched than the driest places on Earth. The prospect that life could have evolved there seemed dim.

Each subsequent mission to Mars has changed that impression in surprising ways. Mariner 9 revealed towering volcanoes, polar caps, and channels apparently cut by water. Systematic observations of the surface and atmosphere by Viking led to a huge increase in our knowledge of the breadth of martian geologic history and the dynamics of the current climate. We had landed on the surface for the first time. Data from the recent Mars Global Surveyor (MGS) have again revolutionized our understanding of the evolution of the planet (Figure 3.1), revealing the importance of the very early development of Tharsis, discovering huge magnetic anomalies from an early magnetic field, and showing evidence for recent or even ongoing climate change. Fundamental information also has been derived from the study of martian meteorites. Detailed analysis of these samples has invigorated the debate over whether life ever arose on Mars.

Are we alone? is one of the most compelling questions in science. Is the development of life a common occurrence or an event that is exceedingly rare? On Earth, wherever water exists in a liquid state, viable organisms have been found. Mars is probably the most compelling place to attempt to answer the question, Did life ever arise elsewhere in the solar system?, because we know now that water once existed (and under some circumstances may exist today) in a liquid state on the surface of Mars, and it likely exists in a liquid state at depth in the crust. While the pre-space-age vision of civilizations on Mars has been replaced with a more informed understanding through exploration and discovery, Mars is still the most compelling and accessible target in the solar system on which to address the question of life's existence beyond Earth.

A synthesis of these discoveries and the results of scientific analyses show that, like Earth, Mars is a planet of contrasts. Both planets have had complex geologic histories and climates that evolved and changed; in both cases

FIGURE 3.1 *(facing page)* Data from the Mars Orbiter Laser Altimeter (MOLA) instrument on the Mars Global Surveyor spacecraft have enabled the construction of highly accurate images of Mars's topography. These two images show the Red Planet's two dissimilar faces. The northern hemisphere *(upper right)* is flat and lightly cratered. In contrast, the southern hemisphere shows extremes of relief and is heavily cratered. Courtesy of the MOLA team.

liquid water played an important role in the evolution of the surface and creation of an environment hospitable to life. Among the planets, Mars is of particular interest because of its similarity to Earth, yet the most important lessons to be learned stem from the differences between the two planets. Mars science might most usefully be thought of as a study of the evolution of an Earth-like planet.

UNIFYING THEMES FOR STUDIES OF MARS

The exploration of Mars has led us to the point of being able to understand the main elements or components of its systems. The sum total of information from spacecraft and telescope observations and from Earth-based research and analysis programs has led to a fairly complete first-order understanding of the planet: the composition and first-order dynamics of its atmosphere, a broad understanding of its water and climate history, its crustal structure as inferred from global gravity and topography, and its surface and crustal chemistry from remotely sensed measurements and the study of martian meteorites. While the individual component systems of Mars have been illuminated, the relationships between them are less well understood. Research addressing these crosscutting questions or themes has the potential to significantly advance our understanding of Mars as a planet. The themes are as follows:

- Mars as a potential abode of life;
- Water, atmosphere, and climate on Mars; and
- Structure and evolution of Mars.

The first theme recognizes that Mars has had in the past on its surface, and may continue to have today in its subsurface, environments with all the ingredients needed to sustain life. Did life ever arise? and Does it exist today? are important first-order questions. To answer these questions, however, we need to know more about Mars and its evolution. If the answer to questions about life is yes, it will be important to know where, how, and for how long life evolved, and its relationship to the planet's evolution. If the answer is no, then it will be equally important to try to understand why life did not arise. Clearly, the answer will be tied to the second theme, the history of volatiles and evolution of the climate and the atmosphere. One way of addressing the question of life will be by searching for a biological imprint on isotopic systems. But to use this type of approach will require a more complete understanding of the atmosphere, the climate and its history, and, of course, water.

Space exploration has taught us that a strong coupling exists between the structure and evolution of planetary interiors and their atmospheres and climates: that is, between the second and third themes. For example, the discovery of localized, very strong remnant magnetism in its ancient crust suggests that early Mars had an active dynamo and a strong magnetic field. If this was the case, it would have shielded the planet from biologically harmful solar (and cosmic) radiation and inhibited the loss of volatiles (water) to space.

One of the distinctive characteristics of Earth relative to other bodies in the solar system is the presence of life. Over the past decade, we have begun to appreciate that life on Earth has been more than a thin veneer of biology passively enjoying the ride; in fact, life has strongly influenced the evolution of Earth. Clearly Mars is not as biologically active as Earth is, and it may even be inert. However, because Mars preserves part of its ancient geologic record that is now lost on Earth, and because it has an atmosphere, evidence for liquid water at some time on its surface, and an ancient magnetic field, it provides a window into the early history of the evolution of an Earth-like planet and perhaps the origins of life.

MARS AS A POTENTIAL ABODE OF LIFE

Present Life

The surface of Mars today is cold, dry, chemically oxidizing, and exposed to an intense flux of solar ultraviolet radiation. These four factors are likely to limit or even to prohibit life at or near the surface of the martian regolith.

Temperature is of interest not only because of its controlling influence on microbial metabolic rates but also because of its influence on the stability of liquid water. Although the peak daytime surface temperature near the martian equator can rise above the freezing point of water during much of the year, the average surface temperature is about 220 K, well below the freezing point of water. Liquid water is essential for life as we know it. Water is abundant on Mars, but not in liquid form.[1] Water vapor and ice crystals are present in the atmosphere, and water ice is almost certainly present within the martian regolith at high latitudes and at the surface in polar regions. At increasing depth, where the rock is warmer as a result of the planetary geothermal gradient, liquid water may be present in pore spaces.[2]

To date, a single set of robotic studies has searched for extant life on Mars: the Viking life-detection experiments, which were designed to test for organisms that used as their carbon source either carbon dioxide or organic molecules. Though the results obtained by the three sets of experiments are regarded as having shown the materials tested to be devoid of both organic compounds and evidence of life,[3,4] this interpretation has been subject to debate.[5]

The lack of agreement highlights the difficulties inherent in the detection of viable microorganisms by robotic means. Indeed, even were there unanimity that the Viking experiments did not show the presence of life, the experiments could still be criticized as being overly "geocentric" in that they showed a lack of evidence of metabolism only of those types particularly common among terrestrial microbes, not of all conceivable metabolisms (nor even of various redox-reaction-based microbial metabolisms well known on Earth).

The problem of distinguishing between biological and nonbiological organic compounds is also complicated. The carbonaceous chondrites, interplanetary dust particles, and probably other bodies within the solar system contain abundant organic material that is structurally similar to biological products. Definitive resolution of the differences between biotic and abiotic organic molecules requires highly sophisticated techniques well beyond any that could be managed robotically.

The accepted interpretation of results from the Viking landers is that the surface materials tested were devoid of organic molecules and of any other evidence of life.[6] However, even without consideration of alternative interpretations,[7] the Viking results cannot be taken as indicating that life does not currently exist on Mars. Organisms at the Viking sites might have been missed because the experimental conditions (e.g., the nutrients provided or processes followed) were not chosen correctly. Even more importantly, martian life might reside in aqueous oases, such as any recently active volcanic vents or fumaroles distant from the Viking landing sites, or at depths far beneath the surficial regolith sampled by the Viking experiments.

Past Life

The surface environment of Mars may not always have been as hostile to life as it is today. Early in the planet's history, the average temperature may have been warmer and the atmosphere more dense, and liquid water may have existed at the surface. The geomorphologic evidence, especially valley networks, indicates that the martian climate was wetter, warmer, and appreciably more hospitable to life prior to about 3.5 billion years ago than it is at present. Fossil evidence of past martian life, if there was any, may be preserved in surface water-laid deposits such as lake- or streambed sediments, in evaporitic mineral pans,[8] and in hydrothermally deposited mineral crusts (Figures 3.2a and b).

An important zone that seems likely to have been habitable throughout martian history is the crustal subsurface, where water may exist in a liquid state. The geothermal gradient of Mars is probably such that liquid water is present at depths as shallow as 2 km near the equator.[9] The discovery of terrestrial microbes living deep within the Columbia River basalts in the U.S. Pacific Northwest and elsewhere on Earth,[10] at depths as great as 3 km,[11] is consistent with the possible presence of microbes living in similar settings on Mars. Samples from hypothetical subsurface settings of life would be very difficult to access, yet such materials may have been dislodged and brought to the surface by meteoritic impacts.

A study of the martian (SNC) meteorite ALH84001 produced evidence suggestive of biological activity on Mars about 3.6 billion years ago.[12] This conclusion has not been widely accepted; the report has engendered much discussion, both pro and con, regarding each of the several intriguing indicators of life proposed.[13]

FIGURE 3.2a An aerial view of the Grand Prismatic Hot Spring in Wyoming's Yellowstone National Park. The color variations are due to pigments in thermophyllic microbes residing in the waters. Such systems are being studied to understand the limits of life on Earth and as possible analogs for environments where life may have existed on Mars. Image courtesy of Russ Finley, Island Park, Idaho.

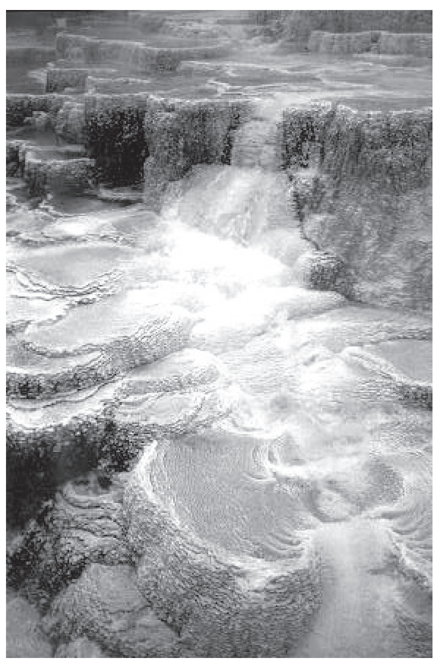

FIGURE 3.2b Travertine deposits at the Minerva Terrace, Mammoth Hot Springs, Yellowstone National Park. Such deposits are intimately associated with microbial communities, aspects of which are commonly preserved in the travertine deposits. Hot springs and their deposits are being studied to understand the limits of life on Earth and as possible analogs for environments where life may have existed on Mars. Image courtesy of Russ Finley, Island Park, Idaho.

Environmental Context for Life

The question of life on Mars must transcend a search for actual organisms. It must include the question of whether the martian environment is or ever was hospitable to the beginning of life. This is a broad and complex question, and the evidence may be so deeply buried in the past that it can be answered only by gaining an extensive and deep knowledge of Mars. For example, on Earth, enzyme-driven metabolic processes can create characteristic biogenic isotopic signatures (affecting, in particular, the ranges of compositions of the stable isotopes of carbon, sulfur, nitrogen, hydrogen, and possibly iron). However, in order to use such isotopic measurements to test for the past presence of life on Mars, we need to know the scope of abiotic fractionating processes there. The search for life should be based on the premise that to understand the potential habitability of Mars, we must fully understand the planet's present and past states. We should be as prepared for a negative answer regarding Mars's potential habitability as for a positive one. The importance of a positive answer is clear, but a negative answer would prompt inquiries into what the implications are for the planetary differences between Earth and Mars.

Key Questions

Questions with potential for a paradigm-altering discovery related to the question of life on Mars include the following:

- Does life currently exist on Mars?
- Did life ever exist there?

A question with potential for a pivotal scientific discovery is—

- How hospitable was and is Mars to life?

Future Directions

The most important future activities with respect to the question of life on Mars are as follows:

1. Sample-return missions will be required to permit definitive tests in terrestrial laboratories for present and past life on Mars (see section "Priorities and Recommendations" below); robotic missions preceding the sample-return missions will assist in locating the most fruitful sites to be sampled.
2. A broad program of study of the Mars environment, present and past, is needed to understand the context in which life did or did not arise on that planet.

WATER, ATMOSPHERE, AND CLIMATE ON MARS

Water

The topics that comprise the theme of water, atmosphere, and climate on Mars are closely linked. As on Earth, water exists on Mars in many states and participates in a broad range of important physical, chemical, and possible biological processes. Water has played a key role in the evolution of the martian climate and in the shaping of Mars's geological history.

The question of where water is on Mars today is difficult to answer fully. We have direct observations of four exposed martian water reservoirs, which include water vapor in the atmosphere, water ice in the atmosphere, seasonal water ice deposits at the surface, and permanent water ice deposits at the polar caps. Of the four, the martian polar caps are by far the most massive. Recent MGS MOLA topographic profiles indicate that the mass of water ice contained within Mars's north and south polar caps, assuming a high ice-to-dust ratio, is the equivalent of a global water layer 22 to 33 m thick.[14]

Beyond the water reservoirs that now can be detected on Mars, there is good reason to suspect the presence of hidden water reservoirs whose combined masses should be much greater than those of the reservoirs that are currently exposed.[15] In Mars's near-surface regolith, it is expected that water is adsorbed on soil particles, and there is fragmentary evidence from the Viking Gas Exchange experiment that the mass fraction of that water could be on the order of 1 percent. Viking and MGS observations have provided geomorphic evidence that the layered deposits surrounding the north and south polar caps also contain water ice, but its mass fraction is currently not well constrained. It is also expected that near-surface ground ice is to be found on Mars, as on Earth, and numerous geomorphological indicators support this idea.[16] Models predict that it should be present within the top meters of the surface at latitudes as low as 20 degrees from the equator in favorable locations.[17]

Because of Mars's low surface temperatures, the partitioning of water is heavily biased toward its condensed phases, causing the martian atmosphere to be extremely dry and ineffective at transporting large quantities of water on seasonal time scales. Liquid water on Mars is not expected to be stable on Mars today, because temperatures exceed 273 K only at low latitudes during the warmest periods of the day, and any liquid generated would quickly evaporate and be transported by the atmosphere to colder locations where it would then freeze.

Some of the most exciting questions concerning Mars deal with the past distribution and behavior of water. Many of these questions are motivated by geomorphic evidence such as runoff channels, outflow channels, and other features that have been interpreted to mean that liquid water may have been present periodically on the surface of Mars in past epochs.[18] The recent MGS Mars Orbiter Camera and Mars Orbital Laser Altimeter observations have provided evidence for large channels that once flowed from the southern highlands to the northern lowlands,[19] widespread ancient layering inferred by some to be of sedimentary origin,[20] and small gullies on crater walls that are considered to be evidence for recent erosion by fluids (Figure 3.3).[21]

Atmosphere

Our knowledge of the composition of the Mars atmosphere is based on measurements of minor gases such as neon, krypton, and xenon and ratios of common isotopes in the ambient atmosphere ($^{36}Ar/^{38}Ar$, $^{12}C/^{13}C$, $^{16}O/^{17}O$, $^{16}O/^{18}O$, $^{14}N/^{15}N$, $^{2}H/^{1}H$) by the Viking descent mass spectrometer, ground-based and airborne spectroscopy, and laboratory analysis of atmospheric gases captured in the vitreous components of martian meteorites. It is thought that a combination of impact erosion and long-term atmospheric loss from the top of the atmosphere by solar-wind sputtering and other processes, and possibly sequestration of CO_2 and other gases in the crust of the planet, are responsible for the present low atmospheric pressure at the surface of Mars (the yearly average is ~6 mbar).

Mars's present-day lower atmosphere is dominated by the behavior of CO_2, water vapor, and dust, as driven by the Mars/Sun configuration and by the interactions of CO_2, water vapor, and dust with the surface. A combination of the above, together with issues of transport and cloud physics, constitutes Mars meteorology. Seasonal changes in the atmospheric mass of CO_2 are up to 30 percent in the current epoch. Water vapor also interchanges with clouds and surface materials; its average annual column abundance is ~10 to 40 precipitable microns of water at north midlatitudes.

Very little is known about the upper atmosphere of Mars. However, the interactions between Mars's upper atmosphere and the impinging solar wind and solar ultraviolet light appear to have played a significant role in the evolution of the martian atmosphere and in the transition from a warmer and wetter environment to the present-day colder and drier environment. Only by understanding the processes that can occur in the upper atmosphere can we fully understand what drove the changes in the volatile inventory and in the climate and thereby understand the evolution of habitability on Mars.

The only in situ measurements of atmospheric composition came from the Viking descent neutral mass spectrometers. These provided two midlatitude vertical profiles, in the altitude range of about 120 to 200 km, of CO_2, CO, N_2, O_2, and Ar densities during low-solar-activity conditions. Using the scale heights thus measured, atmospheric temperature profiles were deduced. These temperatures showed quite large variations and averaged <200 K. Some indirect and limited information on composition and temperatures has been obtained using airglow and ionospheric information. The upper-atmospheric temperatures appear to vary by about 150 K between solar cycle minimum and maximum conditions. The z-axis accelerometer carried by the MGS provided a great deal of important information about total densities and temperatures during its extended aerobraking period.[22]

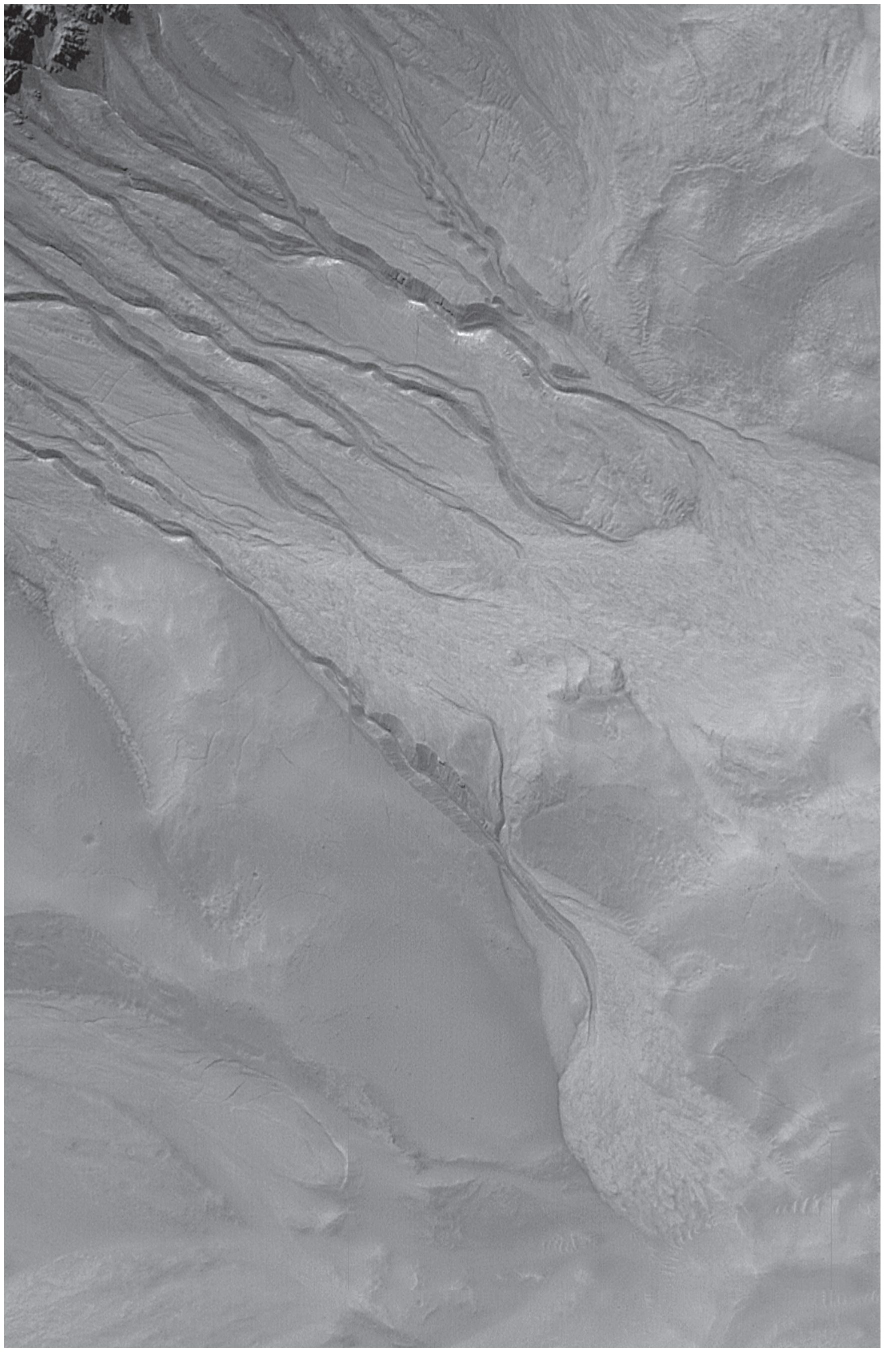

FIGURE 3.3 The Mars Orbiter Camera on Mars Global Surveyor imaged these channels in a crater in the region East Gorgonum (37.4° S, 168.0° W). These features have been interpreted by some researchers as being due to the recent flow of water across the surface. The numerous channels and apron deposits indicate that many tens to hundreds of individual events involving the flow of water and debris have occurred here. The channels and aprons have very crisp, sharp relief, and there are no small impact craters on them, suggesting that these features are extremely young relative to the 4.5-billion-year history of Mars. The image is 2.3 km wide, and illumination is from the upper left. Mars Global Surveyor, Mars Orbiter Camera, Release No. MOC2-241, courtesy of NASA/JPL/Malin Space Science Systems.

The only in situ measurements of the thermal plasma composition, density, and temperature in the ionosphere of Mars were obtained by the retarding potential analyzers carried aboard the two Viking landers, along with the mass spectrometers mentioned above. Electron density altitude profiles were also obtained by several U.S. and Soviet spacecraft (e.g., Mariner 9), using the radio occultation technique. Thus, we have some information on both the dayside and near-terminator-nightside electron density values, covering the altitude range of about 120 to 300 km. No clear presence of an ionopause was seen in this database.

Climate

Climate encompasses a broad range of complex, interacting systems with a wide range of time scales. The Mars climate system, which includes the surface, atmosphere, polar caps, and accessible regions of the subsurface, has undergone significant change during the planet's history. Three time scales of climate variability can be considered: interannual, quasi-periodic, and long term.

Multidecade telescopic records of great dust storms, multiyear surface pressure records acquired at the Viking landing sites, multiyear orbiter observations of the appearance of the seasonal and residual polar caps, and large variations in atmospheric water make it clear that the climate of Mars exhibits distinct variations from one year to the next (interannual changes). Understanding the nature and causes of these variations is important for identifying interactions among the cycles of carbon dioxide, dust, and water in Mars's present climate.

One of the cornerstones of our understanding of the climate of Earth is that small, quasi-periodic variations in Earth's orbital and axial elements over time scales of tens to hundreds of thousands of years result in large-scale changes in Earth's climate.[23] Mars's orbital and axial elements experience variability on time scales that are comparable to those of Earth, but the magnitudes of these variations for Mars are significantly greater.[24] The consequent changes to the insolation at high latitudes undoubtedly have caused significant changes in the seasonal cycles of carbon dioxide, water, and dust. Based on our present understanding, Mars is the planet in the solar system that is likely to have experienced the most significant quasi-periodic variations in its climate (Figure 3.4).

A wide range of surface features on Mars can be interpreted as evidence for warmer climatic conditions at various times in the planet's history (long-term climate change). There is general consensus that Mars possesses all the volatile ingredients necessary to produce a warm and wet climate, but the problem is that at Mars's distance from the Sun, the stable location for Mars's volatiles is not in the atmosphere but in condensed phases, which makes it difficult to maintain a stable martian greenhouse.[25]

Although the earliest martian atmosphere was probably lost by impact erosion and hydrodynamic escape during the Early Noachian era, a relatively robust atmosphere appears to have been reestablished during the Noachian by primitive volatiles released during the creation of the Tharsis Plateau by volcanic and igneous processes. The end of the Noachian marked a huge change in the climate and probably in the volatile inventory of Mars. Erosion rates declined, valley network formation largely ceased, and magmatism declined. The intrinsic magnetic field appears to have declined or ceased at that time; the loss of the protective magnetic field may have allowed substantial solar-wind erosion of the atmosphere, with a consequent change in climate.[26]

Key Questions

Questions with potential for a paradigm-altering discovery related to water, atmosphere, and climate on Mars include the following:

- What are the sources, sinks, and reservoirs of volatiles on Mars?
- How does the atmosphere evolve over long time periods?

Questions with potential for a pivotal scientific discovery include the following:

- Is there an active water cycle on Mars?
- What are the dynamics of the middle and upper atmosphere of the planet?
- What are the rates of atmospheric escape?

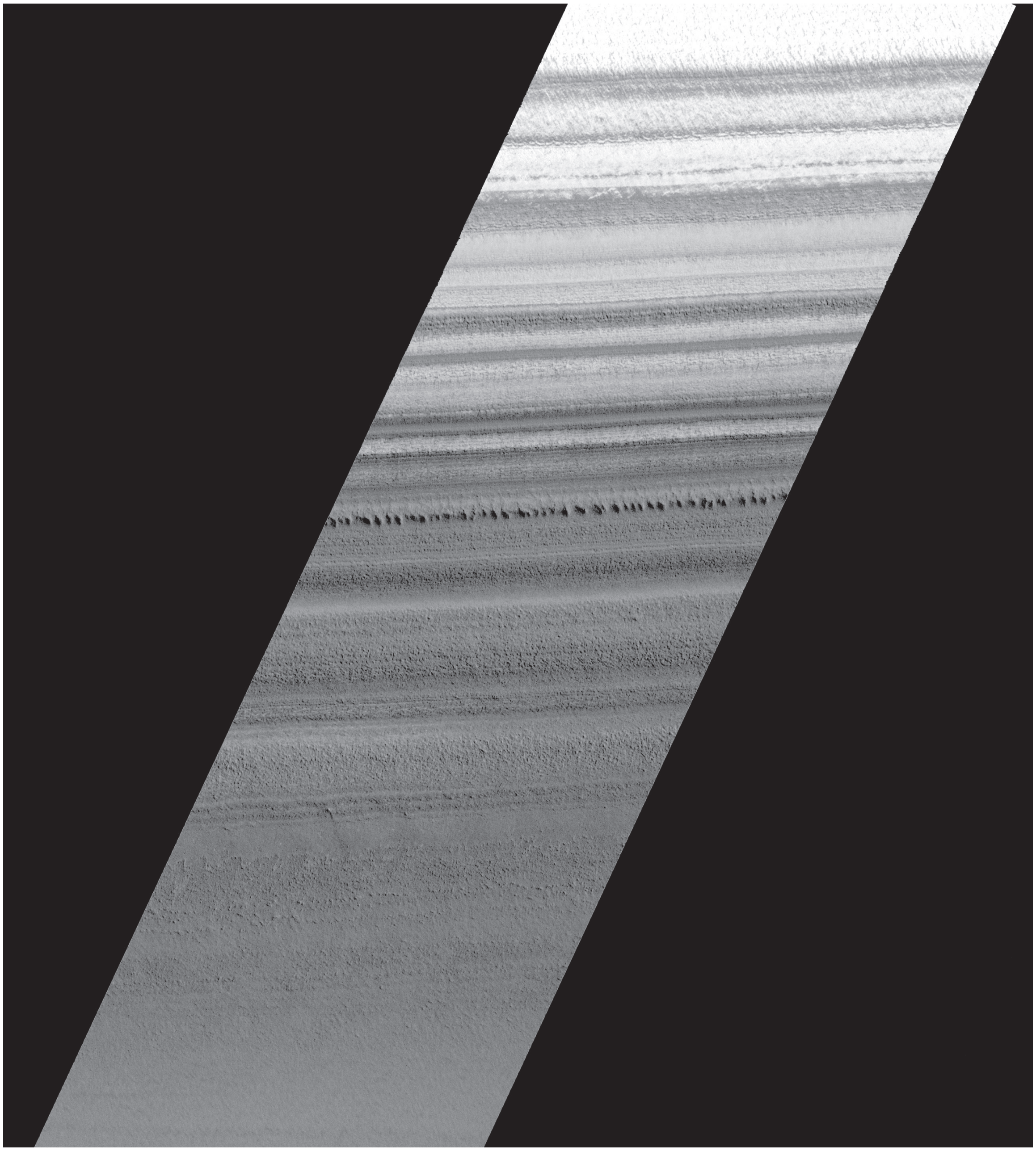

FIGURE 3.4 The Mars Orbiter Camera on Mars Global Surveyor imaged the alternating layers of bright and dark material comprising the North Polar Cap. This image of one of the dark lanes crossing the cap reveals internal layering. This layering is thought to consist of mixtures of water ice and dust, with the albedo variations indicating different dust concentrations in an ice matrix. The apparent regularity of the variations with depth may be indicative of quasi-periodic variations in the martian climate. The image (86.48° N, 279.54° W) shows a region 1.66 km wide, and the vertical relief from the top of the image to the bottom is approximately 350 m. MGS MOC, M0002100, courtesy of NASA/JPL/Malin Space Science Systems.

A question whose answer would contribute to building the foundation of knowledge of the solar system is—

- What is the three-dimensional distribution of water in the martian crust?

Future Directions

Important directions for the future relating to Mars's water, atmosphere, and climate are the following:

1. The ground-level chemical and isotopic composition of the atmosphere, including humidity, should be tracked for at least a martian year at a network of lander stations.
2. The distribution of water (in both solid and liquid form) in the crust, globally or at a wide variety of sites, should be established (e.g., by sounding radar).
3. The composition and dynamics of the middle and upper atmosphere and the rate of escape of molecules from the atmosphere should be measured.

STRUCTURE AND EVOLUTION OF MARS

Structure and Activity of the Crust and Interior

Major advances in our understanding of the interior of Mars have come recently in four important areas:

- The bulk composition of Mars is better constrained owing to a greatly improved estimate of the moment of inertia made possible by Pathfinder measurements.[27] The moment of inertia depends on the distribution of density within a planet, and only a limited range of rock compositions have a given density.
- Mars had a magnetic field in the past, but there is no present global field, as shown by high-amplitude magnetic anomalies detected in the southern highlands of Mars by the Mars Global Surveyor.[28]
- Crustal thickness variations are fairly smooth across the dichotomy boundary between the northern and southern hemispheres of Mars; thus, an impact origin for the low-lying northern hemisphere is not favored.[29] The crustal thickness results are consistent with a plate tectonic hypothesis, but they do not confirm that idea.
- A key insight from the MGS topographic data is that the Tharsis Plateau predates the formation of apparently fluvial channels. This suggests that the outpouring of lava to make the plateau may have released enough carbon dioxide to form an insulating atmosphere and sufficient water to form the channels and even an ocean.[30]

Composition of the Crust and Interior

Most of what we know about the composition of Mars comes from three types of measurements: (1) in situ analysis of the rocks and regolith by landers, (2) orbital observations by emission and reflectance spectroscopy, and (3) studies of meteorites that are inferred to have come from Mars.

In situ analyses by the Viking and Mars Pathfinder landers found rocks at the Pathfinder site to be more siliceous than the basaltic rocks at the Viking sites.[31] The soil is similar at both sites and less siliceous than rocks at either. Measurements from the Thermal Emission Spectrometer aboard MGS extended these compositions globally; andesitic rock appears to dominate in the northern lowlands and basalt in the older southern highlands.[32]

Members of the SNC category of meteorites, comprising the shergottites, nakhlites, and chassignites, plus the unique meteorite ALH84001, are thought to have come from Mars. Five different rock types are known in the SNC collection. They include basalts and lherzolites (shergottites), clinopyroxenites (nakhlites), a dunite (Chassigny), and an orthopyroxenite (ALH84001). Most appear to be igneous cumulates. None of these rocks matches the composition of the basaltic andesites found at the Mars Pathfinder landing site. Similarly, none samples the surface-atmosphere interface, and they constitute a very inadequate sample of interior compositions.

Chronology and Stratigraphy

The geologic units of Mars are assigned to three major time-stratigraphic systems. The oldest is the Noachian system, which comprises the ancient southern highlands. MGS data indicate that the Tharsis complex of volcanoes was initiated in the Upper Noachian era. Rocks of the Hesperian system overlie Noachian units; these include much of the northern lowlands. The most recent system is the Amazonian, represented by the plains and volcanic materials of Amazonis Planitia.

The absolute ages of Mars's geological events, and thus the time history of the planet's evolution, will be fully understood only when the relative chronology derived from stratigraphy is tied to an absolute chronology. The density of superposed craters provides a means of estimating absolute chronology, but this technique is dependent upon imperfect models of the cratering rate on Mars through time. The flux of cratering projectiles on Mars is uncertain by about a factor of two.[33] This uncertainty has relatively little effect on interpretation of the absolute age of Noachian terrains, expected to have been originally nearly saturated with craters, or of very young terrains, where a surface with a nominal age of ~10 million years is young in any case. However, the factor-of-two uncertainty means that ages of terrains that fall in middle martian history are very poorly constrained.

Isotopic dating of Mars rocks from key stratigraphic levels will be required to establish the absolute chronology of the martian geologic record. The most reliable dates will be obtained from samples returned to terrestrial laboratories; laboratory precision in ages gotten by the K-Ar, ^{39}Ar-^{40}Ar, Rb-Sr, Sm-Nd, and U-Th-Pb techniques will approach 10 million years. In order to extend the range of sites dated beyond those that can be reached by sample-return missions, it may be important to develop a technique of in situ dating, presumably by the K-Ar method, by robotic spacecraft. Using this method in the laboratory to date martian meteorite samples of known radiogenic age, researchers find that K-Ar can be used to date samples in situ to an accuracy of ~20 percent,[34] which for rocks of intermediate age would be a great improvement over the factor-of-two uncertainty in cratering chronology. Whether this technique can be effectively implemented on Mars has not been demonstrated.

Surface Processes

Water, wind, volcanism, and impact cratering have been fundamental drivers of large-scale surface modification on Mars. On a smaller scale, surface materials are altered by reaction with the atmosphere in ways that are poorly understood.

Morphologic features created by running water and, apparently, by standing bodies of water can be seen on Mars. Fluvial features range in size from the giant outflow channels to valley networks to recently identified small, young channels.[35] Features indicative of standing bodies of water range from putative shoreline features in the northern hemisphere, perhaps due to an ocean,[36] to deltaic and intracrater sediments, to finely layered bedding. Sediments deposited in standing bodies of water are high-priority sites for the preservation of fossils and biosignatures.[37] Many of the valley networks terminate in craters, while the outflow channels primarily debouched to the northern plains.

Wind has been a significant force in shaping the surface of Mars. Dunes are ubiquitous features, seen across Mars from orbiter to lander resolutions, while so much of the planet exhibits a mantle of fine-grained material that true bedrock exposures are rare. A better understanding of the importance of eolian processes through Mars's history will require thorough characterization of the current atmosphere and its dynamics, long-term surface observations of the surface and atmosphere at a range of sites, systematic imaging, and returned samples.

The style of volcanism varies in space and time across Mars, ranging from large constructs in the Tharsis region with relatively young surface flows (Figure 3.5), to vast Hesparian ridged plains, to morphologies suggestive of old, explosive volcanism in the central highlands. Our understanding of magma chemistry and absolute chronology is, however, primitive, and it is not yet clear whether the range in volcanic styles represents changes in source regions, changes in near-surface environments, or atmospheric evolution.

Models for the physical and chemical alteration of the martian surface span a wide range of possible mechanisms. The presence of an apparently deeply oxidized ancient crust coupled with apparently unoxidized later volcanic landforms has led to the idea that most of the weathering occurred early, during a warmer, wetter time,

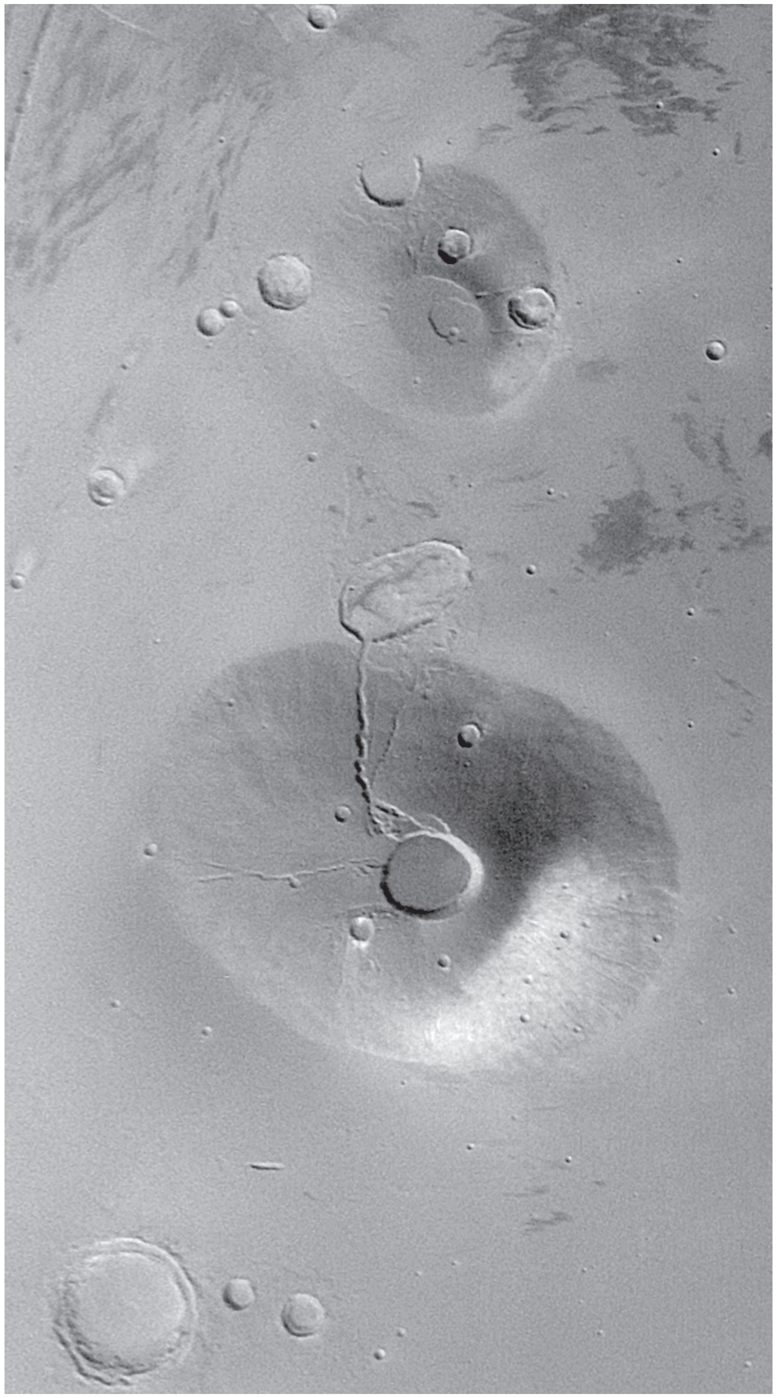

FIGURE 3.5 This wide-angle view from the Mars Orbiter Camera on Mars Global Surveyor shows the martian volcanoes Ceraunius Tholus *(lower)* and Uranius Tholus *(upper)*. The presence of impact craters on these volcanoes, particularly on Uranius Tholus, indicates that they are quite ancient and are not active today. The light-toned area on the southeastern face *(toward lower right)* of Ceraunius Tholus is a remnant of a once-more-extensive deposit of dust from the global dust storm events that occurred in 2001. The crater at the summit of Ceraunius Tholus is about 25 km across. Sunlight illuminates the scene from the lower left. Image courtesy of NASA/JPL/Malin Space Science Systems.

and that alteration has been sporadic since then. Estimated rates of weathering under current conditions are essentially negligible.

Key Questions

Questions with potential for a paradigm-altering discovery with respect to the structure and evolution of Mars include the folowing:

- What rock types comprise the crust of Mars?
- What are the nature and origin of Mars's crustal magnetism?

Questions with potential for a pivotal scientific discovery are as follows:

- What is the degree of internal activity in Mars?
- What is the size of the martian core, and is it partly or wholly liquid?
- What was the origin and fate of the Mars dynamo?
- What is the absolute chronology of the planet?
- How does the oxidation state of the Mars crust vary with depth?

Future Directions

Important directions for the future relating to Mars's structure and evolution include the following:

1. A long-lived network of seismic stations is needed on Mars for determining the structure, properties, and activity of its interior.
2. Heat flow from Mars ultimately should be measured at a series of surface stations.
3. The compositions and ages of crystalline rocks from a distribution of martian sites should be measured. This will best be done by studying returned samples, but the database can be expanded with in situ measurements made by landers.
4. A high-resolution magnetic map of Mars's southern highlands should be made.

INTERCONNECTIONS AND CROSSCUTTING THEMES

The fundamental questions for Mars exploration outlined in this chapter link strongly to the overall themes of this survey report as well as to the themes and directions of several of the other panels. Relative to the overall themes of the survey (Where did we come from? Where are we going? Are we alone?), the scientific and exploration priorities for Mars are strongly linked to the third question. However, it is impossible to properly address this question and understand the true meaning of an answer without a strategy for understanding the evolution of the interior and climate of the planet, which tie into the other survey themes.

A key crosscutting theme for "evolution of an Earth-like planet" is that of coupled atmosphere-surface-interior processes. The evolution of the climate is intimately tied to the release of volatiles from the interior and the protection of an early atmosphere by a magnetic field. As the climate evolves, its signature is recorded in minerals through surface-atmosphere interactions and preserved in weathering rinds and/or concentrated in sedimentary deposits. The isotopic signatures of current gaseous and solid phases, together with signatures preserved in the geologic record, document key elements of this evolution. This clearly cuts across the various themes of reports from this panel and the Inner Planets Panel.

The primary theme for the Inner Planets Panel is "The Inner Solar System: Key to Habitable Worlds." If we consider the solar system as a model for understanding how Earth-like planets form and evolve, then Mars, like each of the inner planets, is a critical piece of the puzzle. Through the exploration of the inner planets and comparative planetology, we have developed a deeper understanding of the similarities and differences in planetary evolution and relationships to the basic physical and chemical properties of the planets. Yet we are still faced with fundamental questions, such as, What led to the unique character of our home planet? How important is relative position in the solar system, or even birth order? What is the real role of planetary size? Why is plate tectonics observed only on Earth? How does a magnetic field affect climate and volatile evolution? How does the presence of a biosphere affect planetary evolution? (We know Earth's biosphere controls the composition of its atmosphere. Comparisons of Venus with Earth underline the difference that this can make.)

The exploration of Mars will feed directly into the major questions defined by the Inner Planets Panel. However, a detailed Mars program is not a substitute for the exploration of the inner planets; Mars is but one "leg of the stool." Just as we cannot truly understand the ramifications and implications of the answer to the question, Did life ever evolve on Mars?, without a comprehensive knowledge of the planet's evolution, so also we cannot address the fundamental questions of the inner solar system without comprehensive knowledge and comparative study of all the planets.

CURRENT NASA AND INTERNATIONAL PLANS FOR MARS EXPLORATION

The pace of Mars exploration for the next decade is breathtaking. A recently released report by the NRC's Committee on Planetary and Lunar Exploration (COMPLEX), *Assessment of Mars Science and Mission Priorities*, reviewed the current state of Mars science, identified critical questions for future investigation, and mapped the congruence between existing and proposed missions and these science priorities.[38] The results are summarized in Table 3.1.

Two important points are evident from this summary. The first is that, including spacecraft currently in orbit around Mars and excluding the Mars Sample Return mission, there are nine missions planned or in operation, some involving multiple assets such as the two Mars Exploration Rover (MER) missions and four landers for NetLander, that will fly before the end of 2009.[a] In addition, a Mars Scout mission will be selected before the end of 2003 to fly in 2007. The range of Mars science that will be addressed by these missions is as broad and deep as the Mars science community, ranging from the upper atmosphere to the deep interior. The second point, however, is that even with this program, there are areas of science that will not be addressed. For example, no plans have been made for conducting absolute dating of the surface by isotopic techniques; nor are there plans to investigate surface-atmosphere interactions in the polar regions.

It has been argued that in order to properly address the highest-priority question for Mars—Did life ever evolve on the planet?—the planetary context is crucial to understanding the implications of a yes or no response. Given the range of investigations over the next decade, this foundation should be achieved. However, within a fiscally constrained program it is still not possible to cover every topic to the level expected by every constituent.

KEY MEASUREMENT OBJECTIVES

On the basis of the current state of Mars science reflected in this chapter as well as in other recent NRC and NASA documents,[39,40] the most important measurement objectives for Mars have been identified and prioritized. The top priority is to obtain data to answer the question Did life ever arise on Mars? This panel concurs with the conclusions of earlier NRC panels that a definitive answer to this question can only be obtained via the study of samples returned to Earth.[41] Returned samples would also serve to support a number of other high-priority studies bearing on the climate and weathering history and geologic evolution of the planet.

To understand the overall evolution of Mars and the interconnections among its systems (interior, surface, atmosphere), which are central to answering the question about life on the planet, key in situ measurements are required. The atmospheric and seismic measurements described above (see the sections "Water, Atmosphere, and Climate on Mars" and "Structure and Evolution of Mars") require landers with long-duration capabilities to establish the presence of internal activity and capture the full seasonal dynamics of atmospheric processes. The

[a]Editor's note: During the period when this report was being prepared for publication, the French-led NetLander mission was canceled.

TABLE 3.1 Comparison of Recommendations of Science Priorities with Experiments on Projected Flight Missions

	Panel Recommending											Inclusion in Missions: NASA						Inclusion in Missions: Other			
Science Priorities	COMPLEX 1978	CPBCE 1990	COMPLEX 1990	COMPLEX 1994	NASA 1995	COMPLEX 1996	McCleese 1996	COMPLEX 1996	COMPLEX 1998	NASA 2000	MEPAG 2000	MGS 1997	MO 2001	MER 2003	MRO 2005	MSL 2009	Sample Return	Nozomi 1999	Mars Express 2003	Beagle 2 2003	NetLander 2007
Interior																					
What is the size and state of the core?	●		●	●							●										●
Is Mars active (interior activity, tectonics, volcanism)?				●							●										●
What is the thickness/structure of the crust?	●		●							●	●	○									
What is the geothermal gradient?	●										●										
What is the character/origin/evolution of the magnetic field?	●		●								●	●									○
Geochemistry and Petrology																					
What variations of geochemistry and petrology are present?	●												●			○	○		●		
What have been mechanisms of geochemical differentiation?		●															○				
Is there evidence for aqueous mineralization?					●								○	○	○	○	●		○	○	○
Chronology and Stratigraphy																					
What are the relative ages of geological units and events?	●	●									●	○	○		○						
What are the absolute ages of geological units and events?	●	●									●									○	
What are the absolute ages of crystalline rocks?	●										●						●			○	
Surface Processes																					
What are the present rates of erosion and deposition?											●	○	○		○				○		
What were the past rates and processes: water and eolian?	●											○	○		○				○		
What has the role of impact cratering been?												○	○		○				○		
What role has volcanism played in surface evolution?											●	○			○				○		
Surface/atmosphere interaction: what volatile sources/sinks?	●										●	○	○	○	○	○			○	○	○
Water																					
Present cycle: sources, sinks, mechanisms, dynamics?	●						●			●					●				●		
What is the 3-D crustal water distribution/origin (liquid/ice)?	●						●			●	●	○			○				○		○
How has the hydrological cycle operated in the past?		●					●				●	○			○						
Life																					
Does life exist on Mars?	●										●					○	●				
Can any chemical products of life be detected?	●		●		●		●				●			○	○		●				
Do isotopic patterns suggest life?							●				●						●				
What can we learn from Antarctic meteorites?						●															
Atmosphere																					
What is the current composition of the atmosphere?	●										●				○				○	○	
What are the circulation dynamics of the atmosphere (T, P)?	●			●			●					●			○				●	○	●
How has the atmosphere changed over time?											●										
What is the radiation environment at the surface of Mars?													●				●				
What is the nature of weather on Mars?	●			●				●			●				●				●	○	●
Climate Control																					
What is the interannual variability of climate?				●							●				○				○		○
What has been the long-term climate history of the planet?											●										
Upper Atmosphere and Plasma Environment																					
What are the dynamics of the upper atmosphere?																					
What are the hot atom abundances and escape fluxes?											●							○	○		
What are the ion escape fluxes?																		○	○		
What are the magnetic field configurations?	●			●														○			
What are the processes controlling the ionospheric energetics?																		○			

NOTE: In the column titled "Panel Recommending," solid circles identify the questions that each panel recommended for study. The column labeled "Inclusion in Missions" shows which missions will address these questions; solid circles signify missions that will concentrate on each science objective, and open circles signify a lesser level of attention to that objective. Missions in NASA's Mars Exploration Program are listed separately from the missions projected by other nations. During the period when this report was being prepared for publication, the French-led NetLander mission was canceled.

dynamics of the upper atmosphere of Mars and rates of atmospheric escape should be studied (among other reasons) to constrain the rates of water loss from Mars, a key factor in the volatile history.

In summary, the measurement objectives that the Mars Panel has identified include the following:

- Definitive measurements to test for the presence of extant or extinct life, or the geochemical and organic chemical evidence for past biological activity. These measurements will require highly sophisticated equipment, procedures, and sample preparation techniques not currently available, nor likely to be available in the foreseeable future, for in situ experiments. Consequently, samples selected from well-documented sites of promising biological potential must be returned to Earth for detailed study.
- Detailed characterization of the geochemistry, mineralogy, trace elements, and chronology of samples selected from well-documented locations and returned to Earth to address questions relevant to the absolute chronology, climate and water history, igneous and metamorphic evolution, and weathering history of Mars.
- Determination of the sources, sinks, and reservoirs of volatiles through integrated measurements of the composition of the atmosphere (including humidity), isotopes of atmospheric gases, and volatile content of and processes in the subsurface, made over at least 1 martian year, using long-lived gas analyzers. Concurrent measurement of the composition of the middle and upper atmosphere is required to provide a systematic understanding.
- Determination of the size of Mars's core, its current internal activity, and its large-scale planetary structure using passive seismometry at a minimum of four sites, operating for at least 1 martian year.
- Determination of the absolute chronology of Mars. Required are the measurement of ages of crystalline rocks from surfaces on at least four strategically chosen geologic units displaying conspicuously different crater densities. This measurement objective can be achieved through sample return if appropriate surfaces are sampled, and/or through in situ age determinations made by landers if the technology can be demonstrated to achieve sufficient precision and accuracy.
- Measurements from orbit of the dynamics of the middle and upper atmosphere of Mars and the rate of atmospheric escape.
- Measurements of the current neutral gas and ion escape fluxes; both optical remote-sensing and in situ instruments carried on an orbiter are required to achieve these objectives.

SUGGESTED MISSIONS

Mars Sample Return

The Mars Panel attaches the greatest importance to Mars Sample Return (MSR), unquestionably a high-cost mission. While MSR cannot replace certain crucial in situ measurements (e.g., heat flow, seismicity, electromagnetic sounding for water, analyses of labile samples, and determination of atmospheric dynamics), it is scientifically compelling in its own right, and the ground-truth acquired from returned samples will aid the interpretation and greatly enhance the value of data from orbital and robotic lander missions. Spacecraft capabilities that would contribute to effectiveness in sampling include mobility, in situ reconnaissance analytical instrumentation, and a core drilling device. (Under current conditions, it appears likely that living organisms, and more generally all organic material, would be destroyed by oxidizing conditions in the surface layer of Mars. They may be preserved only at depth in the planet. Just what depth—centimeters, meters, kilometers—is unknown.) Necessary capabilities include the ability to manipulate and document samples collected and to package them in a way consistent with requirements placed by the planetary protection protocol imposed on the mission. A radioisotope power system for the mission (see below) would expand the geographic range of sites that could be sampled and would extend the mission's stay time, allowing the collection of a larger and more carefully selected suite of samples. Ample power undoubtedly will be important if drilling is contemplated.

It is essential that the site to be sampled be carefully chosen, with the choice drawing upon the large body of orbital and lander data that will be in place by the time the MSR is flown. However, no single sample-return mission will completely satisfy the need for this form of exploration, no matter how carefully it is planned. Mars is highly varied in its geology; prior to returning some martian material to Earth it may be impossible for us to understand which type of site has the highest potential for providing samples that contain evidence of life and other valuable scientific data; sample collection and return represent a new endeavor, one that may not work perfectly the first time. It will be necessary to plan for a series of MSRs over whatever span of time the budget permits.

Mars Long-Lived Lander Network

The Mars Panel also recommends the emplacement of a network of long-lived surface stations on that planet, a moderate-cost mission. The primary purpose of these stations should be to address two questions that the panel believes are neglected by the Mars Exploration Program as currently constituted: (1) the internal structure and activity of the planet and (2) the composition and activity of its atmosphere. Such a mission, or series of missions, has not been designed by NASA, but the French space agency Centre National d'Etudes Spatiales (CNES), in cooperation with international partners, is planning a four-station network science mission with goals that are compatible with the panel's recommendations. Radioisotope power systems will be required to achieve the needed lifetimes and global distribution of the stations.

The Mars Long-Lived Lander Network (ML^3N) would use passive seismometers to explore the structure and activity of Mars. Heat-flow probes also would contribute importantly to our knowledge of the martian interior, but these require the drilling of holes, and they might more logically be emplaced by MSR if that mission has drilling capability; this would avoid placing a drilling requirement on the lander network.

ML^3N should also include meteorological stations that measure pressure, temperature, relative humidity, atmospheric opacity, and wind velocity. Also included should be mass spectrometers that permit high-precision, long-lived chemical and isotopic atmospheric analysis of the chemical dynamics of C, H, and O at Mars's surface. Time variability of isotopic compositions can be interpreted in terms of sources, sinks, and reservoirs of volatiles, and atmospheric evolution. Humidity sensors would track the flux of water vapor into and out of the regolith with time of day and season, providing important insight into the water budget on Mars.

The complement of instruments on the French-led NetLander mission, the four landers distributed around the planet, and the expected lifetime of 1 martian year will be sufficient to constrain the nature and size of the core, seismic activity, seismic velocities of the crust and mantle, and atmospheric properties of pressure, temperature, humidity, and wind speed. They will also have a magnetometer and electromagnetic sounding capabilities to sense crustal structures and to search for subsurface water and ice. While this complement of instruments does not address all of the high-priority goals outlined for the ML^3N, it represents a significant step forward.

Mars Upper Atmosphere Orbiter

The need for an orbital mission to study the upper atmosphere of Mars is identified above (see the section "Key Measurement Objectives"). Areas to be addressed by this low-cost mission are the dynamics of the upper atmosphere; hot atom abundances and escape fluxes; ion escape; minimagnetospheres and magnetic reconnections; and energetics of the ionosphere. A Mars Upper Atmosphere Orbiter (MAO) can explicitly explore these issues in the present-day environment and answer a number of important scientific questions. Furthermore, such a mission could quantify present-day escape processes and allow certain backward extrapolations to earlier epochs in martian history.

The instruments needed for a meaningful attack on these questions would require no new, basic instrument development and could be installed as a partial payload complement of an orbiting spacecraft. The neutral winds can be measured by either a "baffled" neutral mass spectrometer or a Fabry-Perot interferometer. The latter instrument, along with a good ultraviolet spectrometer, could address in a meaningful way the hot atom and neutral escape flux questions. The neutral mass spectrometer would also provide neutral composition and temperature information. A plasma instrument complement consisting of a magnetometer, low-energy ion mass spectrometer (capable of measuring flow velocities and temperatures), an electron spectrometer, a plasma wave detector, and a Langmuir probe would go a long way toward resolving the questions of ion escape, minimagnetospheres and magnetic reconnections, and energetics of the ionosphere.

Mars Science Laboratory

The Mars Exploration Program (MEP) projects development of a Mars Science Laboratory[b] (MSL), presumably a moderate-cost mission, for launch in 2009. Its instrument payload has been stated only in the most general terms. The mission may be important, indeed essential, as a technology-demonstration precursor mission to MSR.

Mars Scout Missions

The Mars Scout program consists of competed, Discovery-class, principal-investigator-led missions with $300 million cost caps. The program was instituted by NASA to meet science goals and opportunities not covered by other missions and to provide a mechanism for the MEP to be responsive to discoveries. As structured, the Scout program provides an excellent opportunity for NASA to accommodate science topics outside the principal objectives of the MEP, and for the broad science community to respond to discoveries and technological advancement. The Mars Panel strongly endorses NASA's desire to structure the Scout program after the successful Discovery program. In that regard, it is essential that the measurement goals for the Mars Scout program be directed toward the highest-priority science for Mars and be selected by peer review. As witnessed by the response to the recent call for Scout proposal ideas (more than 40 submissions were received), tremendous enthusiasm has been stimulated by recent Mars discoveries for addressing scientific investigations not covered by the MEP. Scout provides for the MEP a component that is highly flexible and responsive to discovery, and the panel recommends that Scout missions be flown at every other Mars launch opportunity. Some of the mission priorities defined in this chapter (e.g., the ML^{3}N and MAO missions) could be accommodated in the Scout program as stand-alone missions or as targets of opportunity on international missions. The science priorities outlined in this chapter do not encompass the full range of science topics of great importance to Mars that may fit within the Scout funding and mission profile. These are covered more completely in the NRC report *Assessment of Mars Science and Mission Priorities*,[42] as well as in the recent report of the Mars Exploration Payload Assessment Group (MEPAG).[43]

IMPACT OF SAMPLE RETURN ON THE MARS EXPLORATION PROGRAM

One of the major problems facing the MEP is choices. The abundance of new data across all disciplines has led to extraordinary discoveries about Mars that are being reported in rapid succession, and with the planned program of NASA and international missions, this is likely to continue (see Table 3.1). The compelling nature of the planet and this vigorous exploration program has spawned a deep and broad scientific community whose interests and compelling questions span many orders of magnitude in space and time. Yet despite the apparent richness of this exploration program, the resources for NASA's MEP are nevertheless finite. The scientific community and NASA are therefore faced with the critical question of prioritization.

Central to this debate is the question of sample return, on which there are two points of view. The first view is that the costs of sample return will be high in terms of the spacecraft resources and infrastructure needed to handle, house, and analyze the samples. This investment will undoubtedly defer in situ and orbital investigations of Mars during this effort. This view further advocates that because of this cost, sample return should be delayed until such time as the science questions to be addressed by sample return are so compelling and the technology so mature that success is assured. As the program moves forward then, the MEP resources should be directed toward continued in situ and orbital investigations. For example, the current best estimates of the cost of sample return range between $1.5 billion and $2.5 billion, which would require NASA to combine the resources from two launch opportunities to fit within the MEP cost profile.

It could be argued that for these same resources, four landed science packages with rovers could be sent to some of the many interesting places on Mars, to conduct in situ surface science and life-detection experiments and to establish well-instrumented stations for interior, climate, and meteorology studies. This view that sample return should be delayed is motivated in part by a fear that if sample return is approached too quickly, then all Mars

[b]Also known as the Mars Smart Lander or the Mobile Science Laboratory.

science will be arrested to achieve this goal, and if the first samples are indistinguishable from SNC meteorites, further support for Mars exploration will be jeopardized.

The contrary view is that the most compelling question for Mars exploration, and one that is central to the SSE Survey, is Are we alone?, and that only through the analysis of samples returned to Earth can this question be addressed to any level of certainty. This view also holds that the breadth of Mars science to be addressed by the upcoming missions (see Table 3.1) is enormous and will do much to provide the essential context to address this question. However, the next leap in understanding Mars will only be achieved though the analysis of samples from the surface understood in a planetary context. This view also holds that the first sample return will neither address all questions nor close the book on the life question. However, it will be critical for making the maximum use of the huge investment in data sets made over the preceding decade (such as shown by the lunar example). Subsequent sample-return missions, interleaved with appropriate orbital and in situ exploration, will ultimately drive exploration to the sites that will maximize our understanding of Mars and answer the question Are we alone? This view is motivated in part by the sense that sufficient information exists today to move toward the goal of sample return and that the technological challenges are sufficiently large that the program needs to begin now in order to achieve a launch early in the next decade (2013-2020), and by a fear that without a clear commitment to sample return the MEP will never achieve this goal and will lose support.

The choice of which path to take is not necessarily an either-or proposition. The true costs of sample return are not yet known and will be refined over the next few years. Even with a high cost, there will be abundant other opportunities for Mars exploration. For example, following the flight of Mars Science Laboratory in 2009, the next opportunities to fly to Mars are in 2011 and 2013. If the costs of a simple sample-return mission come in at the low end of the cost estimates ($1.5 billion) and it is flown in the 2013 opportunity, then, according to recent reports of the MEP budget to MEPAG, there should be sufficient resources to fly a competed Scout mission for the 2011 opportunity. If the costs for sample return are too high to bear for the 2013 opportunity, this could be delayed till the 2016 opportunity, and MSR together with competed Scout missions in 2011 and 2013 would easily fit within the current budget climate.

RECOMMENDATIONS OF THE MARS PANEL TO THE STEERING GROUP

Mission Priorities

Mars Sample Return

The Mars Panel attaches the highest priority to missions that will collect samples on Mars and return them to Earth, beginning at the 2011 opportunity if this is possible. Observations made by robotic orbiters and landers beyond 2005 cannot alone answer the most important questions regarding Mars: whether life ever started on that planet, what the climate history of the planet was, and why Mars evolved so differently from Earth. The definitive answers to these questions will come from the study of Mars samples, in the context of orbital and surface in situ measurements, of known provenance in laboratories on Earth.

The Need for Sample Return—The Search for Life. At our present state of knowledge and technological expertise, and probably for the next several decades, it is unlikely that robotic in situ exploration will prove capable of demonstrating to an acceptable level of certainty whether there once was or is now life on Mars. Results obtained from any life-detection experiment carried out by robotic means are likely to be ambiguous for these reasons:

- Results interpreted as showing an absence of life will be challenged because the experiments that yielded them were too geocentric or otherwise inappropriately limited;
- Results consistent with, but not definitive of, the existence of life (e.g., the detection of organic compounds of unknown, either biological or nonbiological, origin) will be regarded as incapable of providing a clear-cut answer; and

- Results interpreted as showing the existence of life will be regarded as necessarily suspect, since they might reflect the presence of earthly contaminants rather than of an indigenous martian biota.

Similarly frustrating results can be expected in attempts to search robotically for either of the two categories of fossil life that might be preserved on Mars: stromatolites and microfossils. Stromatolites are accretionary organosedimentary structures, commonly thinly layered, produced on Earth by the activities of mat-building communities of mucilage-secreting microorganisms. Unfortunately, true stromatolites on Earth can be confused with nonbiologically deposited look-alikes (e.g., in thin, sometimes wavy layers of mineral precipitates commonly found in caves and hot spring deposits on Earth; on Mars, such deposits may have been laid down, for example, by repeated wetting and drying or freezing and thawing of mineral-charged salt pans or shallow lagoons). If stromatolite-like structures were photographed on the surface of Mars, it seems certain that there would be widespread uncertainty as to whether the objects detected were in fact produced by life. Similarly, it seems unlikely that robotic detection of objects resembling microfossils in or on the surfaces of rocks on Mars would prove sufficiently convincing to demonstrate to an acceptable level of certainty that past life existed on that planet.

The Need for Sample Return—Geochemistry. In the area of geochemistry and mineralogy, thin sections of returned samples can be prepared in terrestrial laboratories and studied by microbeam techniques as well as optically. Rocks contain a near-infinite amount of information on a microscopic scale, some of it crucial to an understanding of the rock's origin and history. Rocks can be disaggregated, and their constituent minerals can be studied chemically and isotopically. The data obtained provide strong clues about and constraints on the nature of the differentiation events that led to the formation of the rock. They also make possible a variety of approaches to precisely dating igneous rocks in the sample collection. Information about the Mars climate will be found in the layer of weathering products that are expected to be found on rock samples. These products will almost certainly be very complex minerals or amorphous reaction products that will tax the best Earth-based laboratory techniques to understand. It is very unlikely that anything but a highly qualitative and ambiguous description of the weathering products could be made by robotic instruments operating on the martian surface.

The Need for Sample Return—Climate and Coupled Atmosphere-Surface-Interior Processes. Some surface-atmosphere and climate processes involving labile elements or compounds must be studied in situ. Nevertheless, the key measurements for understanding the relative loss of portions of the atmosphere to space and to surface reservoirs are the compositions of surface minerals and their isotopic systematics. Atmospheric-loss processes (e.g., hydrodynamic escape, sputtering) leave characteristic isotopic signatures in certain elements. Loss to space versus to surface weathering (e.g., CO_2 to carbonate minerals) is likely to produce isotopic fractionation in different directions. The ratio of ^{15}N to ^{14}N in the martian atmosphere is understood to have evolved over the past 3.8 billion years (it is currently 1.6 times the terrestrial value), and a determination of this ratio in near-surface materials may constrain the time of their formation. Compositional and isotopic analysis of surface minerals, weathering rinds, and sedimentary deposits will establish the role of liquid water and processes such as weathering. The corresponding measurements on volatiles released from near-surface materials are likely to be more heterogeneous and may provide fossils of past atmospheric and chemical conditions that allow the past climate to be better understood.

Martian Meteorites—Not a Substitute for Sample Return. The SNC meteorites do not obviate the need for sample-return missions. SNC meteorites have provided a tantalizing view of a few martian rocks and a demonstration of how much can be learned when samples can be examined in Earth-based laboratories; however, they represent a highly selected subset of martian materials, specifically, very coherent rocks of largely igneous origin from a small number of unknown locations. Thus, SNC meteorites are unhelpful in answering one of our outstanding questions—What is the absolute chronology of Mars?—because although they can be accurately dated, the geologic units from which they are derived are unknown. While returned samples are also a selected subset of martian materials, their geologic context will be known, and they will be from sites selected because they can provide particularly valuable information.

Regarding the climate history of Mars and possible life there, the samples that will provide the most information are not igneous rocks, as the SNC meteorites are, but sediments and soil samples. Taking Yosemite Valley as a terrestrial analog, the SNC meteorites represent the cliffs rather than the river muds and the sediments from the outwash stretching into California's Central Valley. It is the latter materials that can provide information about chemical conditions, biological processes, and timing; their martian analogs, geologic features that have the properties of river and lake deposits, will help most in understanding water and life on that planet.

Mars Long-Lived Lander Network

The Mars Panel considers that the ML^{3}N should be the second-priority Mars mission. The principal experiments on these landed stations should be passive seismometers and analyzers of the ground-level atmosphere, both of which must continue to record data for at least a year to achieve their potential. Earlier NASA advisory panels consistently recognized the importance of these experiments and recommended their implementation.[44]

Seismic data can determine the size of the core, which will constrain the bulk composition of the planet, as will information on the seismic velocities in the mantle. Knowing the bulk composition of Mars is important for understanding the origin of the planets. Seismology can tell us whether the core is all solid, all liquid, or part solid and part liquid (as is Earth's core), which has a direct and profound bearing on our understanding of planetary dynamos and the present-day lack of a Mars global magnetic field.

In the area of martian atmospheric science, there are open questions of meteorology, atmospheric origin and evolution, chemical stability, and atmospheric dynamics. These questions are of particular interest for a broad community of scientists, because useful comparisons with Earth can be made that may prove important for understanding the atmospheric evolution of both planets.

The Mars Panel attaches high priority to a better understanding of the martian atmospheric composition, chemistry, circulation, and concentration of near-surface water vapor as the key components of climate systems and for comparative studies of atmospheric dynamics and evolution.

Mars Upper Atmosphere Orbiter

The third priority of the panel is given to the Mars Upper Atmosphere Orbiter mission. The upper atmosphere of Mars drives the lower atmosphere in a variety of ways, and very little information is available on the martian upper atmosphere. There are no existing plans in the current U.S. Mars Exploration Program to address any of the scientific questions that are listed above concerning the upper atmosphere of Mars (see the subsection "Mars Upper Atmosphere Orbiter"). Japan's Nozomi and Europe's Mars Express will address these questions to some extent, but much more data will be needed to meaningfully elucidate these open issues. Both the Nozomi and Mars Express will arrive at Mars during solar cycle minimum conditions, and data from solar cycle maximum are required in order to answer some of the outstanding questions (e.g., nonthermal escape).

Unprioritized Missions

Mars Science Laboratory

The MSL mission may be important, indeed essential, as a technology-demonstration precursor mission to MSR, but the panel saw little science for MSL that cannot be done as well or better by the missions discussed above. The detailed examination and analysis of rock samples can be done far more capably in terrestrial laboratories (though admittedly MSL could perform simpler analyses of a larger and more dispersed set of samples than those that an MSR mission could return). The ML^{3}N mission could conduct much more comprehensive atmospheric and seismic studies than could MSL, which is a single mission, not a network. K-Ar ages remotely measured by MSL, if this technique can be made to work, will provide only one data point toward calibrating the martian geological column, with accuracy inferior to that obtained on MSR samples in terrestrial laboratories.

Since the panel's task was to prioritize science missions and since it sees MSL largely as a technology-demonstration mission, it has not included MSL among the prioritized missions.

Mars Scout

The program of Mars Scout missions provides an excellent opportunity for NASA to accommodate science topics outside the principal objectives of the Mars Exploration Program and for the broad science community to respond to discoveries and technological advancement. If this activity is to be modeled after the successful Discovery program, it is essential that the science goals for Mars Scout missions be directed toward the highest-priority science for Mars selected by peer review.

There is concern in the Mars science community that Scout missions may be vulnerable to being sacrificed in times of budget stringency. The panel urges that the Mars Scout program be maintained with a high level of protection.

Technology Development

Sample return will not be a simple task, and it has not been achieved by a robotic mission other than the Russian sample return from the Moon 30 years ago. For the much more difficult sample return from Mars, many technologies will have to be developed, tested, and validated. These include hazard avoidance in landing, sample selection, handling and delivery to the transfer chamber, the Mars Ascent Vehicle, orbit rendezvous and capture, transfer to Earth, and quarantine on Earth. It will be essential for precursor missions to MSR to incorporate the testing of essential technologies.

Sample return and a long-lived surface network will require sophisticated instrumentation for science and operations. While much thought has been given to what sort of instruments might be required, there has been less direct investment in the development of instruments and demonstration of the technology required for flight-qualified systems.

An extremely important consideration in establishing the capabilities of landed packages on Mars, static or roving, is the power supply on which they rely—the options being solar panels and radioisotope power systems (RPSs). The Viking landers lasted as long as 7 years because they had RPS power. The twin MER 2003 rovers, with solar panels, will operate for no longer than an estimated 90 days. This is because as the elevation of the Sun changes, the available solar power decreases; for the same reason, the rovers get colder and need more power to keep warm. Meanwhile, dust is accumulating on the panels, further reducing the power. The MER rovers are also restricted by the needs of their solar panels to land in the 10° N to 15° S latitude belt at relatively low elevations.

The ML^3N described above will not be able to operate within these constraints; an RPS will be essential. The power problem will seriously affect sample-return missions as well. Reliance on solar power would mean that samples will almost certainly have to be collected at low latitudes, which excludes those parts of Mars where ground ice is stable and where other volatiles are most likely to be present. If the sample-return mission has a rover to collect samples, its lifetime will be short. The use of a drill to collect samples would require a generous supply of power.

Data Analysis, Ground-Based Observations, and Laboratory Studies

The Mars Exploration Program, with its missions at 2-year intervals, presents a new problem in fully exploiting the amount and variety of data that will be collected. The volume and quality of data returned by MGS alone have been extraordinary, and the analysis of these data is only beginning. With the rapid pace of Mars missions planned for the next decade, the flood of data can be expected to increase.

While the Mars Exploration Program consists of flight missions, exploration and understanding of the planet as a system also depend on other modes of data acquisition. Some examples follow.

Telescopic Studies

Continuing telescopic observation of Mars has played a key role in demonstrating that the surface of Mars changes on a relatively short time scale (as with seasonal changes, dust storms, evolution of the polar caps.) Telescopic and spacecraft data are highly synergistic, and each plays a role in supporting the other. Support for future robotic and possible manned missions to Mars will require a long climatological baseline. The long baseline, partially obtained with ground-based and HST telescopic data, will also contribute to an understanding of the water cycles between the atmosphere, regolith, and polar caps, as well as spatially resolved data on volatile cycles of water, carbon dioxide, carbon monoxide, and ozone.

Theoretical Models

Models are an essential component of any scientific endeavor. Examples of theoretical planetary studies are those that treat the geodynamics of Mars, its interior structure, atmospheric loss and fractionation, and global climate and general circulation models.

Martian Meteorites

As already mentioned, the SNC category of martian meteorites plays an important role in studies relating to martian life and the planet's structure and evolution. Studies of this small group of meteorites in terrestrial laboratories have provided invaluable, if fragmentary, information about the geochemistry and chronology of Mars. NASA, the National Science Foundation, and the Smithsonian Institution have jointly supported an Antarctic meteorite program since 1976, in which teams of experts search areas known to contain a concentration of meteorites for 6 weeks every austral summer; support of this program should continue.

Astrobiological Research

Studies of deep-sea hydrothermal environments, hot springs, the deep subsurface, alkaline or acidic environments, and sea ice have revealed amazing microbial diversity in the form of uncultured organisms from environmental extremes. Some of these habitats are potential analogues to past and present martian environments where life may have arisen or might continue to exist. Through expanded knowledge about the potential diversity of the microbial world, we can explore how ancient microbial life might have impacted planetary processes on Mars.

Preparations on Earth for Sample Return

A series of NASA and NRC panels have considered the special problems associated with bringing samples from Mars to Earth,[45-49] and NASA has acknowledged the need to prevent forward and back contamination at every stage of the process of delivery. This includes the need to construct a quarantine facility to receive and contain the samples.

A recent NRC report drew attention to the long lead time required to prepare a Mars Quarantine Facility (MQF) for the reception of Mars samples once they are delivered to Earth.[50] On the basis of prior experience with terrestrial biocontainment facilities and the Apollo Lunar Receiving Laboratory, the authoring committee estimated that 7 years would be required to design, construct, and staff the MQF. To this must be added the time needed to clear an environmental impact statement and to carry out several NRC recommendations for reconnaissance studies that are needed to inform the design and operation of the MQF.[51] The aggregate of time required will strain the schedule even of a 2011 launch (2014 return). It is important that scientific research and design studies that must precede the design and construction of a Mars Quarantine Facility begin immediately, and design and construction of the facility should begin at the earliest possible time.

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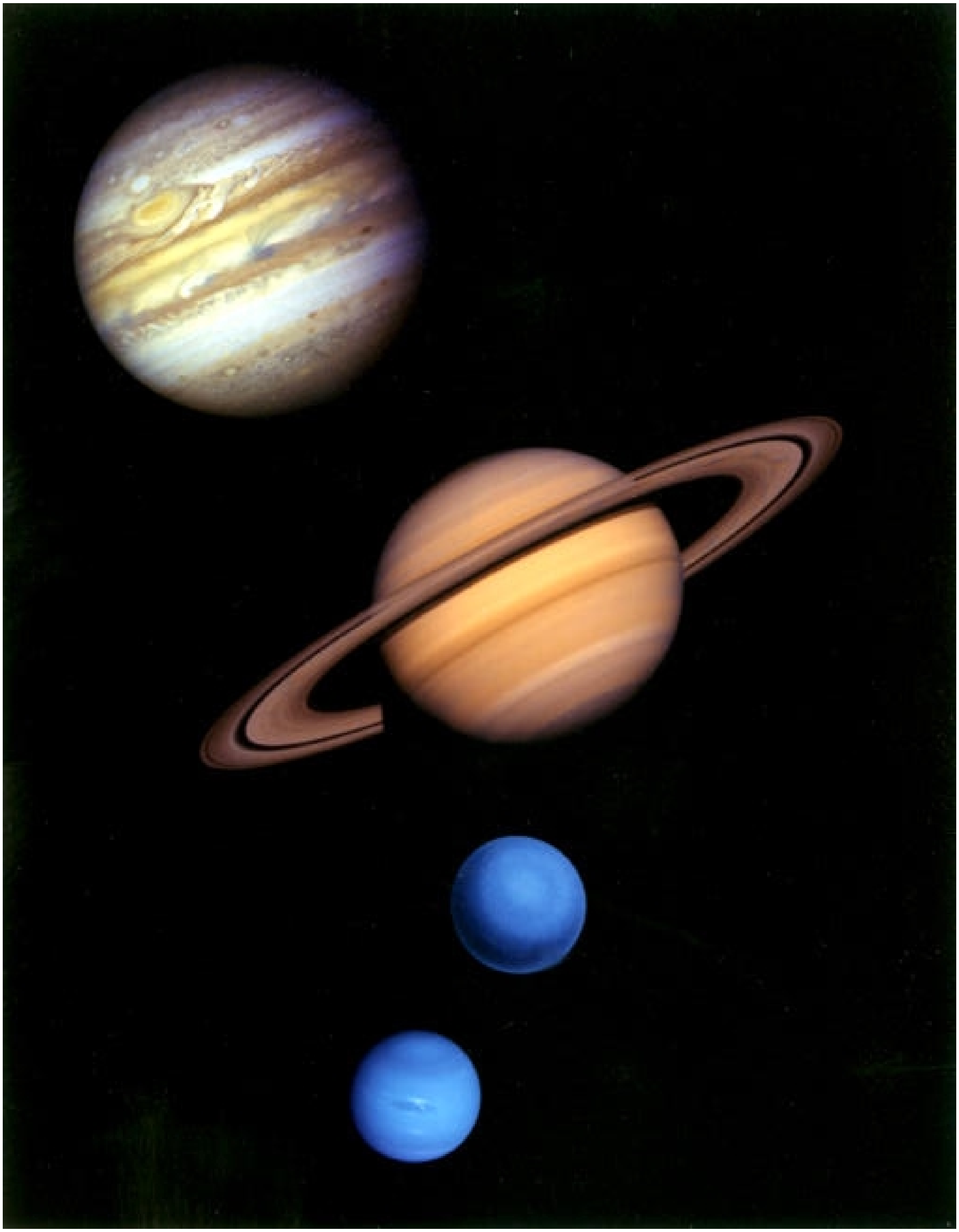

4

Giant Planets: Keys to Solar System Formation

The giant planet story is the story of the solar system. Earth and the other small objects are leftovers from the feast of giant planet formation. As they formed, the giant planets (Figure 4.1) may have migrated inward or outward, ejecting some objects from the solar system, pushing some into their parent stars and swallowing others. Smaller than stars, which have their own nuclear furnaces, the giant planets contain ~95 percent of the planetary mass of the solar system. Their hydrogen-helium atmospheres are similar to those of cooled-down mini-Suns, but their rock-ice cores may resemble those of terrestrial planets.

The differences in composition and internal structure among the giant planets reveal differences in how they formed. The "gas giants" Jupiter and Saturn are mostly hydrogen and helium. These planets must have swallowed a portion of the solar nebula intact. The "ice giants" Uranus and Neptune are made primarily of heavier stuff, probably the next most abundant elements in the Sun—oxygen, carbon, nitrogen, and sulfur. The core of each giant planet is likely the "seed" around which it accreted nebular gas.

Giant planets are laboratories in which to test our theories about geophysics, plasma physics, meteorology, and even oceanography in a larger context. Jupiter's bottomless atmosphere, with its 300-year-old storms and 500-km/h winds, piques our interest because it is so different from Earth's atmosphere. The giant planets' enormous magnetic fields and intense radiation belts test our theories of terrestrial and solar electromagnetic phenomena. The rings are puzzles, each ring system different from the others, reflecting different origins and environments. So far, the main lesson of applying theories developed for Earth to the giant planets is humility.

Giant planets are also our link to the cosmos. Many have been found around other stars. We know something about their orbits and masses, and we will soon know the radius, temperature, albedo, and partial composition for several of these objects. To interpret these data, we must understand the giant planets in the solar system. The two data sets are complementary. Extrasolar giant planets tell us how unusual we are—How many other stars have planets and possibly planetary systems like our own? The solar system's giant planets provide calibration standards. We can study them in situ, and we can calculate what they would look like from the distance of a nearby star. Together these two lines of research address the questions, Where did we come from? Where are we going? Are we alone?

FIGURE 4.1 *(facing page)* A montage of the solar system's four giant planets. Shown to scale, they are *(top to bottom)* Jupiter, Saturn, Uranus, and Neptune. Courtesy of NASA/JPL.

UNIFYING THEMES FOR STUDIES OF THE GIANT PLANETS

Giant planets may be studied as whole objects whose formation affected everything else in the solar system, as meteorological laboratories, as ringed worlds surrounded by pulsating magnetospheres, and as standards for calibrating observations of planets around other stars. The ideas discussed in this section are encompassed by the following three themes:

- Origin and evolution,
- Interiors and atmospheres, and
- Rings and plasmas.

ORIGIN AND EVOLUTION

Isaac Newton (1642-1727) used the motions of the Galilean satellites to determine Jupiter's mass. William Herschel (1738-1822) was aware that Jupiter's density was anomalously low. In the 20th century it became clear that only the lightest elements, hydrogen and helium, could account for the low density. The inferred H/He ratio was similar to that of the Sun. From spectroscopy of H_2 and CH_4 came the inference that the C/H ratio at Jupiter is similar to that of the Sun. These studies gave rise to the solar composition model of giant planets: take a piece of the Sun, cool it down to planetary temperatures, and you have a giant planet like Jupiter or Saturn.

Modified Solar Composition Model

The solar composition model does not work for Uranus and Neptune, which are twice as dense as Saturn even though they are smaller and therefore suffer less self-compression. Their densities are consistent with a mixture of water, methane, and other ices at high temperatures and pressures. Since oxygen and carbon are the third and fourth most abundant elements in the Sun after hydrogen and helium, this led to the modified solar composition model. It starts with a mixture of elements similar to that of the Sun, but then the hydrogen, helium, and other noble gases are blown away. Stars like the Sun go through an active ("T Tauri") phase when they are young. The powerful stellar winds during the T Tauri phase are capable of blowing the gases out of the system. The mixture that remains has solar composition except for the missing gaseous component. If the nebula is too hot, the ices too are lost, and only the rocks and metals remain. This modified solar composition model is supported by meteorite composition, in which the elements that form solids at planetary temperatures are present in solar proportions.

Timing is critical. Giant planets have to form before the solar wind sweeps the gases out of the solar system. That might explain the difference between the ice giants, Uranus and Neptune, and the gas giants, Jupiter and Saturn. Giant planets form faster at the orbits of Jupiter and Saturn, where the density of the solar nebula is large and collisions are more frequent. Perhaps Uranus and Neptune were just starting to accumulate gases when the T Tauri solar wind blew the gases out of the solar system.

The time that it takes to produce a Jupiter-sized object depends on how it forms, and here some uncertainty exists. The slow way is to first accrete a rock-ice core of approximately 10 Earth masses. Such a core could form by precipitation of less volatile materials as the solar nebula cools. The solid particles settle to the equatorial plane of the circumsolar disk and then coalesce by collisions. The dense solid objects are able to attract gas once they reach the critical size of about 10 Earth masses, but the rate is limited by how fast the growing object can radiate its energy. The fast way to form a Jupiter-sized object is by hydrodynamic instability. Somewhere in the solar nebula the density reaches a critical value, and the mixture collapses from its own gravitational self-attraction. Stars form this way when the density in giant molecular clouds reaches a critical value. A Jupiter-sized object formed by the second process (without a core) would be similar to a brown dwarf—a substellar object, insufficiently massive to sustain thermonuclear reactions in its core.

The way to choose between these hypotheses is to determine if all the giant planets have cores. Three out of four do. Jupiter is the uncertain one.[1] Measuring the size and mass of Jupiter's core is therefore a major objective.

Volatile Abundances

The temperature of the solar nebula at various distances from the Sun is critical in determining which compounds were solid and therefore likely to be incorporated into each giant planet and which were not. The Galileo probe found that carbon, nitrogen, sulfur, argon, krypton, and xenon are enriched by similar amounts, two to four times solar abundance. This result was unexpected, because the different elements are not equally volatile. One theory is that all the volatiles condensed together at temperatures below 30 K, at or beyond the orbit of Neptune, and then migrated in to Jupiter's position.[2] Another theory is that the volatiles were trapped in the form of clathrate hydrates in the feeding zone of Jupiter while the nebula was cooling down.[3] The first explanation says that oxygen should also be enriched by a factor of two to four. The second explanation requires a larger enrichment for oxygen (O/H at least eight-times solar abundance), because the clathrate hydrate is mostly water ice and holds only a limited fraction of other molecules.

Unfortunately, the Galileo probe did not go deep enough to measure the planetary abundance of water. The probe entered one of the dry downdrafts, which apparently extend down well below cloud base at 5 to 7 bars—at least to the 24-bar depth at which the probe signal was lost. The other condensables, ammonia (NH_3) and hydrogen sulfide (H_2S), were depleted at cloud base but approached constant values at the deepest levels. H_2O was still increasing with depth at the deepest levels. Measuring the water abundance in Jupiter's atmosphere is thus a major objective.

Cooling History

Models of the interiors predict that giant planets cool slowly. They should still be radiating substantial amounts of internal energy, and indeed, all but Uranus have measurable amounts of heat emerging from their interiors. Either Uranus cooled faster than the other giant planets did and its interior is now cold, or it is cooling more slowly, in which case the interior is hot but the heat cannot get out. For instance, a layered structure with the high-density material near the center would inhibit convection. Uranus is the only giant planet that spins on its side. Whether this unique feature has anything to do with the low heat flux is not known. The 98° obliquity is evidence that the final stage of planet formation was a chaotic process involving collisions of Earth-sized objects capable of altering the angular momentum of bodies the size of Uranus. A gentle rain of small planetesimals would not do it.

Generally, the internal heat radiated by the planets today is compatible with calculations of their cooling histories. The uncertainty centers on possible internal gradients in composition, the extent of convection zones, the equation of state, and the possible gravitational separation of hydrogen and helium as an additional source of internal energy. Internal structure is revealed in the gravity field. The equation of state is studied in the laboratory. And the separation of hydrogen and helium leaves its mark on the He/H ratio in the atmosphere today. The separation can occur only in Jupiter and Saturn, whose internal pressures are so high (>2 to 3 Mbars) that hydrogen becomes a liquid metal. It is thought that a helium-rich phase will precipitate out of the hydrogen-helium metallic mixture when the temperature drops below a critical value. Helium drops settle toward the center of the planet, leaving the layers above depleted in helium. Jupiter, because of its greater mass, cools more slowly and is just entering this stage, according to the calculations. Saturn, which has less mass, has cooled down far enough that its atmosphere should be significantly depleted in helium.

The Galileo probe measured the atmospheric He/H ratio for Jupiter. The value was higher than that obtained from Voyager remote-sensing observations but agreed with the best estimates of solar composition. In other words, precipitation of helium has not yet produced significant depletion on Jupiter. This raises questions about the interpretation of Voyager remote-sensing observations for both Jupiter and Saturn. For the latter, remote sensing is all we have, and it seems to imply that significant depletion has occurred. The Cassini Infrared Spectrograph will resolve helium lines and provide additional data; however, a probe into Saturn's atmosphere would settle the issue.

Extrasolar Giant Planets

An impressive fraction (~5 percent) of stars surveyed to date show evidence of planets. This number and the mass range will increase as more sensitive detection methods come online and planets with longer-period orbits weigh in. The discovery of giant planets in highly eccentric tight orbits (radii <1 AU) around other stars is revolutionary, because it shows that some planetary systems are very different from our own. There is clearly an observational bias to the results, because massive objects close to their stars are easier to detect by current methods. But the results imply either that giant planets can form in the high-temperature environment close to their parent stars, or that they form farther out and migrate in.[4] Either way, the implications are profound. Giant planets can migrate, provided they interact with comparable masses at different orbital radii. Objects in different orbits repel each other: to conserve angular momentum when energy is dissipated, the inner object moves inward and the outer object shifts outward. A giant planet that moves inward may have expelled other giant planets, which are now wandering through interstellar space. It will either expel or devour any terrestrial planets that are in its path.

How can the study of Jupiter, Saturn, Uranus, and Neptune contribute to the study of giant planets around other stars? The solar system provides ground-truth. The extrasolar giant planets have clouds in their atmospheres.[5] Clouds lead to precipitation and release of latent heat. The giant planets close to their parent stars have large day-night temperature gradients. The temperature gradients lead to winds, which affect the temperature field. Clouds, precipitation, temperature gradients, and winds are meteorological phenomena. We know something about these things from studying Earth and other planets. The observations of extrasolar planets—mass, radius, temperature, and composition—will be difficult to interpret unless we draw on our knowledge of giant planets in the solar system. Even that knowledge is incomplete, so further exploration is vital.

Important Questions for Origins and Evolution

Important questions about the origin and evolution of giant planets can be divided into those specifically relating to the solar system's giants and, more generally, those relating to extrasolar planets and brown dwarfs.

Important questions for the solar system's giant planets include the following:

- How did the giant planets form?
- Does Jupiter have a rock-ice core?
- What are the elemental compositions of the giant planets?
- What are the internal structures and dynamics of the giant planets?
- What are the orbital evolutionary paths of the giant planets?

For extrasolar giant planets and brown dwarfs, the important questions are these:

- Around what types of stars are giant planets found?
- Are multiple giant planets common in stellar systems?
- In what ways do giant planets differ from brown dwarfs?
- What are the properties of extrasolar giant planets (radii, effective temperatures, compositions, clouds, moons, winds, magnetic fields, heat flows)?
- How can we use the giant planets in the solar system to calibrate spectroscopic observations (optical, infrared, radio) of extrasolar giant planets?

Future Directions

As identified by the Giant Planets Panel, the most important directions for research on the origin and evolution of giant planets for the next decade are as follows:

• *Probing Jupiter's interior with gravity and magnetic field measurements from polar-orbiting spacecraft.* As with Earth, one can probe the interior with tools from geophysics that utilize seismic, gravity, and magnetic observations. Two kinds of oscillations are relevant: acoustic modes excited by convection or other interior dynamics, and tidal modes excited by the satellites. The tidal bulges show up in the planet's gravity field, which affects the spacecraft orbit. A spacecraft in a low-periapse polar orbit around Jupiter could detect the satellite-induced tides and also improve the determination of the axisymmetric terms in the gravity field. Both measurements contain information about the core.[6] The magnetic field structure provides information about convection in the deep interior, and may also contain a signature of a solid core, in analogy with Earth's magnetic field, which contains the signature of the solid inner core.[7]

• *Measuring Jupiter's deep atmospheric composition with multiple entry probes and microwave remote sensing.* Probes that operate down to the 100-bar pressure level at a variety of latitudes are needed. Remote sensing at wavelengths greater than 10 cm can detect water at depths down to hundreds of bars. The combination of probes and remote sensing is needed to provide both ground-truth and global context. The water abundance bears on how the giant planets got their volatile elements and whether significant migration of planetesimals occurred in the early solar system. It is important to measure the volatile abundances for all the giant planets, beginning with Jupiter.

• *Acquiring and interpreting Earth-based observations of solar system and extrasolar giant planets.* The effects of clouds, winds, and chemistry on the spectra of solar system giant planets need to be determined, taking into account the orientation of the planet with respect to the Sun and the observer. This information will enable us to expand the scope of comparative planetology to include extrasolar giant planets and brown dwarfs.

INTERIORS AND ATMOSPHERES

The giant planets do not have surfaces in the usual sense, but they have what amounts to the same thing from the point of view of an external observer: a barrier to both remote sensing and direct probing. With currently foreseeable technology, this occurs near the 100-bar pressure level. Below this level, properties must be inferred, just as properties of Earth's interior are inferred from near-surface measurements. The methods of inference are the same for any planet; the interiors of the giant planets are relatively unknown only because near-surface data are relatively sparse compared with data for the terrestrial planets. The distinction between interior and atmosphere is largely an operational one at the giant planets, and the two domains are probably more intimately coupled in the giant planets than in the terrestrial planets precisely because the giants lack a conventional surface.[8-11]

Interior Structure

Present models of giant planet interiors are constrained by observed properties, including planetary mass, radius, shape, rotation period, heat flow, gravitational moments, magnetic moments, and elemental composition.[12] The first five of these observable properties are known to sufficient accuracy; the last three are not. Laboratory measurements and theoretical modeling of the properties of hydrogen, helium, and trace elements at very high pressures also provide critical constraints for interior models. Previous spacecraft measurements have provided many of the observable parameters needed for the development of meaningful interior models. However, the uncertainties in both observational constraints and high-pressure material behavior are such that the interior density and temperature structure, the variation of composition and phase state with depth, and the size of a dense central rock-ice core (or even its existence, in the case of Jupiter) cannot be ascertained with confidence.

Our present view of the interiors of Jupiter and Saturn divides each planet into three distinct regions: a dense central rock-ice core with a mass of up to 10 Earth masses at Jupiter and 6 to 17 Earth masses at Saturn, a fluid metallic hydrogen region at pressures greater than about 2 Mbars, and an outer shell of molecular hydrogen.[13] The question of the presence or absence of a dense core at Jupiter is a key missing link in our understanding of Jupiter's interior structure and hence its formation history. Other key unknowns include the nature of the phase transition between metallic and molecular hydrogen, and the presence or absence of "radiative zones" where the deep atmosphere is not fully convective.

Uranus and Neptune are distinct from Jupiter and Saturn in that the former contains a much larger fraction of elements heavier than hydrogen and helium. Their interior structures are more uncertain. Three-layer models have been developed for these planets that include a small central "rock" core, an extensive "ice" region comprising most of the planet, and a methane-rich hydrogen-helium gas envelope. (In this context, "ice" means a mixture of volatile elements whose original form was water, methane, ammonia, and other ice-forming molecules but whose present form is fluid rather than solid and is probably not composed of intact molecules.) The small internal heat flux observed at Uranus may imply that parts of the interior are neither convective nor homogeneous.

Clouds and Composition

Though we still do not know what trace chemicals give the clouds of the gas giants their familiar colors, we have learned a great deal about the bulk composition and structure of their visible atmospheres from Earth-based and spacecraft-based remote sensing.[14] Different wavelengths probe different levels of the atmosphere, and this fact has been exploited to place constraints on the pressure levels, bulk compositions, and other properties of the various cloud and haze layers. The clouds of Jupiter and Saturn are thought to comprise three distinct layers, composed of ammonia at the top, ammonium hydrosulfide in the middle, and a water-solution cloud at the bottom. Analogous cloud decks may also exist at the ice giants, Uranus and Neptune, with the addition of a methane cloud at high altitudes and perhaps a hydrogen-sulfide cloud rather than an ammonia cloud just below.[15] The Galileo entry probe at Jupiter, while confirming many of the results of earlier remote-sensing observations, found little or no evidence of the expected water and ammonia clouds in the 1- to 5-bar pressure range,[16] probably as the result of entering an anomalous atmospheric hot spot. The resolution of this uncertainty is critical not only to our understanding of Jupiter's origin and evolution, as described in the previous section, but also to jovian meteorology.

The giant planet atmospheres are so cold that volatile species such as water, hydrogen sulfide, and ammonia condense. Methane is sufficiently volatile to be present as a gas throughout the upper atmospheres of the giant planets, though it too can partially condense at Uranus and Neptune. Methane molecules are broken apart at high altitudes by ultraviolet solar photons and by precipitating magnetospheric charged particles, and the fragments can react to form more complex hydrocarbon molecules, producing the array of organic molecules that have been observed in the upper atmospheres of the giant planets. A better understanding of this process may provide clues to how heavy organic molecules, including biogenic molecules, originated on early Earth. At Jupiter and Saturn, ultraviolet photons can penetrate to levels where ammonia, phosphine, and perhaps sulfur-bearing gases are present, giving rise to additional photochemistry. Studying these photochemical and thermochemical processes at the giant planets will guide the interpretation of spectra obtained from brown dwarfs and extrasolar giant planets.

An extended layer of haze particles envelops the upper atmospheres of the giant planets. The hazes are probably produced by auroral chemistry in the polar regions and by photochemistry throughout the upper atmospheres. Global high-altitude winds may carry polar hazes to lower latitudes. The haze is interesting not only because of its influence on atmospheric optical properties, thermal structure, and global circulation, but also because of the possibility of synthesis of unusual and complex organic molecules.

The impact of Comet Shoemaker-Levy 9 on Jupiter in 1994 dramatically illustrates the fact that new material is being introduced into giant planetary atmospheres. The externally supplied oxygen from comets, interplanetary dust, and satellite/ring debris is observed as H_2O and CO_2 in the upper atmospheres, and provides clues about the exchange of material between different parts of the solar system.

Thermal Structure

Just above the clouds lies the tropopause, the coldest layer of the atmosphere. Below this level the temperature increases with depth in a manner that is generally consistent with upward convective heat transport from an internal source. Above the tropopause, the temperature increases with height as the atmosphere is increasingly exposed to solar radiation. However, the observed increase of temperature in the stratosphere is greater than predicted on the basis of solar absorption alone, especially at Neptune, implying additional heating mechanisms.

In the upper stratosphere, molecular diffusion begins to affect atmospheric composition as the density of species heavier than hydrogen falls off rapidly with height. Because these heavier molecules (primarily hydrocarbons) are responsible for cooling the stratosphere by infrared radiation, the temperature rises rapidly with altitude, reaching a plateau of 400 to 1000 K in the thermosphere. The thermospheric temperatures at all giant planets are higher by a factor of two to four than would be expected on the basis of solar extreme-ultraviolet (EUV) heating.[17] Additional high-altitude heat sources are clearly operating. Possibilities include ionospheric Joule heating, charged particle precipitation, and dynamo action.

In the upper atmospheres of the giant planets, the impact of EUV solar photons and magnetospheric charged particles produces ionization, as it does on Earth. The finite electrical conductivity of the ionosphere gives rise to spectacular and dynamic auroral displays that reveal the electrodynamic coupling of the atmosphere with the magnetosphere and with the embedded satellites. As at Earth, ionospheric structure is affected by upper-atmospheric winds, magnetic-field structure, and electric fields induced by motions of plasma. In contrast to Earth, however, planetary rotation plays a dominant role in driving and shaping the upper atmosphere and ionosphere. Spacecraft radio occultations have revealed dramatic spatial (and probably temporal) variations of ionospheric structure at all giant planets, and the relative roles of chemistry and dynamics in producing the observed behavior are not well understood.

The upper atmospheres of the giant planets provide natural laboratories where we can test and refine our understanding of ionospheric structuring and auroral processes that occur under very different boundary conditions at Earth and elsewhere in the universe.

Winds

The cloud patterns are constrained by winds that blow parallel to lines of constant latitude. Instead of one eastward jet stream in each hemisphere, as at Earth, Jupiter has six or seven. The large-scale weather patterns are remarkably stable. The Great Red Spot has been in existence since at least 1664 and possibly much longer.[18,19]

Remarkably, the winds do not decrease as one moves outward in the solar system—Neptune's winds are 3 times stronger than Jupiter's, even though the power per unit area, both from sunlight and from internal heat, is about 20 times less at Neptune than at Jupiter.[20]

Principal questions revolve around the depth of the winds, the role of internal heat versus solar heat in driving them, and the mechanisms that maintain them. For instance, the Great Red Spot and the large jet streams regularly devour smaller spots, but where the smaller spots get their energy is still a mystery.

Atmospheric dynamics is intimately connected with thermal structure and composition. The energy sources for atmospheric dynamics include internal heat, solar insolation, and, at the highest levels, auroral Joule heating and charged-particle precipitation. The internal energy source evidently dominates atmospheric dynamics at and below the cloud level, and the influence of rapid planetary rotation is obvious in the preponderance of zonal (east-west) winds.

Condensation, evaporation, and transport of cloud-forming species also drive the meteorology of the giant planets through their effect on pressure gradients and the redistribution of energy, primarily in the form of latent heat. The Galileo orbiter observations of water-rich convective storms associated with lightning and cyclonic shear zones have shed new light on the role of moist convection in the maintenance of zonal jets on Jupiter; thus, knowing the abundance of water is a major objective for jovian meteorology.[21]

The zonal jets are visually prominent at the gas giants Jupiter and Saturn and less so at the ice giants Uranus and Neptune.[22-25] At Jupiter, zonal wind speeds (at the cloud level) are greatest at the boundaries between the lighter-colored "zones" of upwelling warmer atmosphere and the darker-colored "belts" of sinking cooler atmosphere. Wind maxima on Saturn are shifted relative to the banded contrasts, and the wide prevailing eastward equatorial jet has wind speeds reaching ~500 m/s, a significant fraction of the local sound speed. Uranus and Neptune, by contrast, have a prevailing westward wind near the equator and eastward winds at high latitudes, with top speeds again in the range of several hundred meters per second. The existence of such winds at Uranus is particularly puzzling in view of the fact that Uranus, unlike the other three giants, apparently has no significant internal heat source and a highly asymmetrical pattern of solar heating. In the other giants, large-scale vortices in the wind pattern revealed by cloud patterns have lifetimes ranging from months to decades in most cases, to centuries (at least) in the case of Jupiter's Great Red Spot. The longevity of these structures is not understood.

At the Galileo probe entry site, the zonal winds increased with depth, lending support to the hypothesis that the zonal jets extend deep into Jupiter's atmosphere.[26] Further measurements of deep atmospheric winds and interior structure are needed to determine how the observed atmospheric winds relate to motions, including possible nonuniform rotation, in the deep atmospheres and interiors of the giant planets.

Key Questions

Important questions about the interiors and atmospheres of giant planets include the following.

Interiors

- What is the nature of convection in giant planet interiors?
- How does the composition vary with depth?
- What is the nature of phase transitions within the giant planets?
- How is energy transported through the deep atmosphere? Do radiative layers exist?
- How and where are planetary magnetic fields generated?

Atmospheres

- What energy source maintains the zonal winds, and how do they vary with depth?
- What role does water and moist convection play?
- How and why does atmospheric temperature vary with depth, latitude, and longitude?
- What physical and chemical processes control the atmospheric composition and the formation of clouds and haze layers?
- How does the aurora affect the global composition, temperature, and haze formation?
- What produces the intricate vertical structure of giant planet ionospheres?
- At what rate does external material enter giant planet atmospheres, and where does this material come from?
- What can organic chemistry in giant planet atmospheres tell us about the atmosphere of early Earth and the origin of life?

Future Directions

The most important directions for research on the interiors and atmospheres of giant planets for the next decade are identified as follows:

- *Resolving fine-scale structure of the gravity and magnetic fields to elucidate the interior structure and the mechanisms of energy transport, magnetic-field generation, and convection within Jupiter.* The acquisition of high-order gravitational and magnetic moments, combined with satellite tides and possibly observations of acoustic oscillations within the atmosphere, will enable us to "image" the deep atmosphere and interior of Jupiter. Deep winds, if they are strong enough, will show up in the gravity field, because their centrifugal forces cause a rearrangement of masses in the deep interior.[27] These observations will provide critical constraints for models of interior structure, energy transport, fluid motions, and magnetic-field generation that have far-reaching planetary and astrophysical applications. Improved observational constraints will qualitatively enhance our understanding of planet formation and evolution and our ability to understand similarities and differences among our own giant planets, extrasolar giant planets, and brown dwarfs.
- *Measuring condensable-gas abundances (H_2O, NH_3, CH_4, and H_2S), temperature, wind velocity, and cloud opacity down to the 100-bar pressure level at Jupiter.* The Galileo probe provided critical information on

elemental abundances in Jupiter's atmosphere, but the limited depth and unusual location of its entry prevented a definitive measurement of the deep tropospheric water abundance. The water abundance is especially critical, not only because it distinguishes among different planet-formation scenarios, but also because condensation of water and the resulting release of latent heat drive atmospheric dynamics. The Galileo measurement of ammonia abundance is also uncertain, owing to experimental problems related to the behavior of ammonia within the mass spectrometer. Ammonia is a critical cloud-forming molecule in the atmospheres of Jupiter and Saturn, and remote sensing of its abundance has yielded contradictory results. Multiple in situ probes and microwave sounders can resolve these issues. Multiple probes can also provide clues to many outstanding questions about atmospheric temperature profiles, tropospheric dynamics, and cloud structure.

• *Acquiring Earth-based telescopic observations of atmospheric composition, structure, clouds, circulation, aurorae, and acoustic oscillations.* Earth-based (or orbital) observations at high spectral and spatial resolution can reveal the three-dimensional distributions of composition, temperature, and winds. These three variables are intimately related. Composition affects the absorption of solar radiation and the re-emission of infrared radiation, thus regulating the thermal structure. Composition and thermal structure affect condensation and release of latent heat, thereby affecting the wind pattern. The winds in turn affect composition and thermal structure by transporting material and heat. To understand how these interconnected processes operate, we need simultaneous observations of temperature, composition, and winds. This is difficult even at Earth, let alone at the giant planets. Previous telescope and spacecraft observations have put several pieces of this complex puzzle in place, but three-dimensional information is still limited. Greater access to large ground-based and space-based telescopes and advances in instrument technology in the next decade should greatly improve the situation. Observations of global acoustic oscillations, although difficult to obtain, are of particular interest because they shed light on interior structure.

• *Performing laboratory and theoretical studies of the behavior of matter under the extreme conditions present in giant planet interiors and atmospheres.* The thermodynamic, kinetic, radiative, and spectral properties of the relevant gases and ices, and the high-pressure equation of state of the relevant hydrogen-helium mixtures are critical to the interpretation of data on both solar system and extrasolar giant planets. Observations need to be combined with theoretical models in order to understand the underlying physical and chemical processes. Laboratory data are critical for analyzing observational data and planning future observations.

RINGS AND PLASMAS

Disks are ubiquitous in the universe, and the solar system's giant planets provide numerous examples amenable to in situ study. These range from visible rings composed of macroscopic objects dominated by gravity, to fully ionized plasma disks dominated by electromagnetic forces, with intermediate cases ("dusty plasmas") where both forces are competitive. The diversity of present-day disk structures at the giant planets offers glimpses into the various stages of solar system formation and other astrophysical processes.

At first glance it is less than obvious that studies of planetary rings will tell us anything about astrophysical disks because of the great mismatch in the relevant spatial and temporal scales on which they operate. Nevertheless, great similarities exist. Most of the underlying physics is scale-invariant, and while it is true that there are important differences between circumstellar disks and rings—for example, the presence of gas in early types of the former and the absence of gas in the latter—their dynamics are essentially the same. Moreover, the study of the dynamics of a disk of particles in the absence of gas provides one essential ingredient in understanding the dynamics of a disk of particles in the presence of gas.

Rings

Among the solar system's four known ring systems, more differences than similarities exist. Saturn's spectacular rings contain by far the most mass of all the rings. Uranus's narrow dark strands are interspersed with small, dusty particles. Jupiter's rings are exceptionally tenuous, and Neptune's rings contain possibly long-lived arc structures. The complexity and variety of structure in the various ring systems, as revealed in the Voyager images and occultations, came as a complete surprise.[28]

The theoretical life span of any of the observed ring systems is much shorter than the age of the solar system. Angular momentum transfer between rings and nearby satellites causes ring particles to fall inward, as does gas drag from the upper reaches of the planet's atmosphere. Interaction of small charged grains with magnetospheric particles and fields can produce inward or outward migration as well as erosion. Continual bombardment by interplanetary particles should darken the rings. Although the rings of Uranus are indeed quite dark, those of Saturn are as bright as fresh ice.

Where did rings come from in the first place? Are they leftover bits of material that did not get swept up into the planet or satellites? Are they the result of the catastrophic destruction of a satellite? Are they remainders of an errant comet that strayed too close to the planet and was torn apart by tidal forces? Or are they continuously replenished by material sputtered from nearby satellites by magnetospheric ions? Knowledge of ring dynamics and particle properties can help to answer these questions.

Recent studies have identified complex gravitational interactions among the rings and their retinues of attendant satellites. There are elegant examples of Lindblad and corotation resonances (two different types of eccentricity resonances first invoked in the context of galactic disks), electromagnetic resonances, spiral density waves and bending waves, narrow ringlets that exhibit internal modes due to collective instabilities, sharp-edged gaps maintained by tidal torques from embedded moonlets, and tenuous dust belts created by meteoroid impact on or collisions among parent bodies. These processes can account for some of the features observed within the ring systems and in so doing can provide the beginning of an explanation for the survival of the rings beyond their predicted life spans.

The composition, size, and shape of the particles remain major unknowns. Infrared spectroscopy and microwave radiometry reveal that Saturn's rings are mostly water ice. Different regions of the rings show noticeable color variations on all scales. The compositions of the rings of Jupiter, Uranus, and Neptune are unknown but apparently different from one another. The jovian ring system shares the reddish color of the nearby satellite Amalthea, but the brightness of the particles is unknown because their scattering cross section is unknown. The uranian rings are nearly colorless, and those of Neptune are so dark that nothing is known about their color.

The study of extrasolar protoplanetary disks can be influenced by studies of planetary rings in the solar system. The concept of the migration of bodies due to angular momentum exchange with surrounding material was first advanced in the ring context and is now a mainstay of planetary formation models. The fine structure of planetary rings with embedded bodies has motivated and guided studies that have application to disks of much larger scale.

Plasmas

The giant planets have redefined our concept of planetary magnetospheres. Unlike the terrestrial planet magnetospheres (Earth and Mercury), the giant planet magnetospheres are internally driven, powered by planetary rotational energy that is extracted by plasma of internal origin.[29] Jupiter's magnetosphere (Figure 4.2) is the largest and the most rapidly rotating and therefore the most powerful and the most different from Earth's. Jupiter's rotational energy is extracted and dissipated by plasma originating in Io's volcanoes. The transport and energization of this Iogenic plasma gives rise to an astonishing variety of remotely observable emissions across the electromagnetic spectrum from radio to x-rays.[30] Most of these emissions have strong spin-period modulations that are presumably analogous to those of astrophysical pulsars.[31]

Major unknowns include the mechanism(s) by which Io injects magnetospheric plasma and the way(s) in which this plasma is energized and transported outward to power the magnetosphere and ultimately to generate a planetary wind. These processes leave distinctive footprints in the planetary auroral emissions that are resolvable from Earth or Earth orbit. However, in situ measurements at low altitudes and high latitudes are needed to provide the key for extracting information about magnetospheric processes from Earth-based auroral images (Figures 4.3 and 4.4).

Saturn's magnetosphere is a smaller analog to Jupiter's, but more complicated because the internal sources of plasma are multiple and widely dispersed. Saturn is unique in the solar system in having a magnetic dipole moment that is almost exactly aligned with its spin axis. Reports exist of pulsar behavior at Saturn which, although

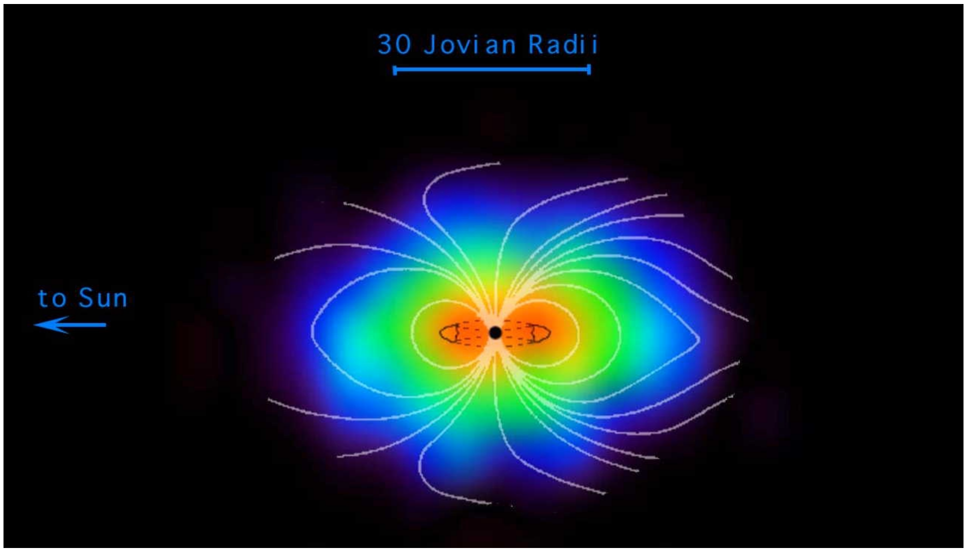

FIGURE 4.2 Jupiter's vast magnetosphere as imaged from a distance of 10 million km by the ion and neutral-atom camera aboard the Cassini spacecraft during its Jupiter flyby in December 2000. Also shown, schematically, is Jupiter's magnetic field and, to scale, the Io torus and Jupiter itself. Courtesy of NASA/JPL/APL.

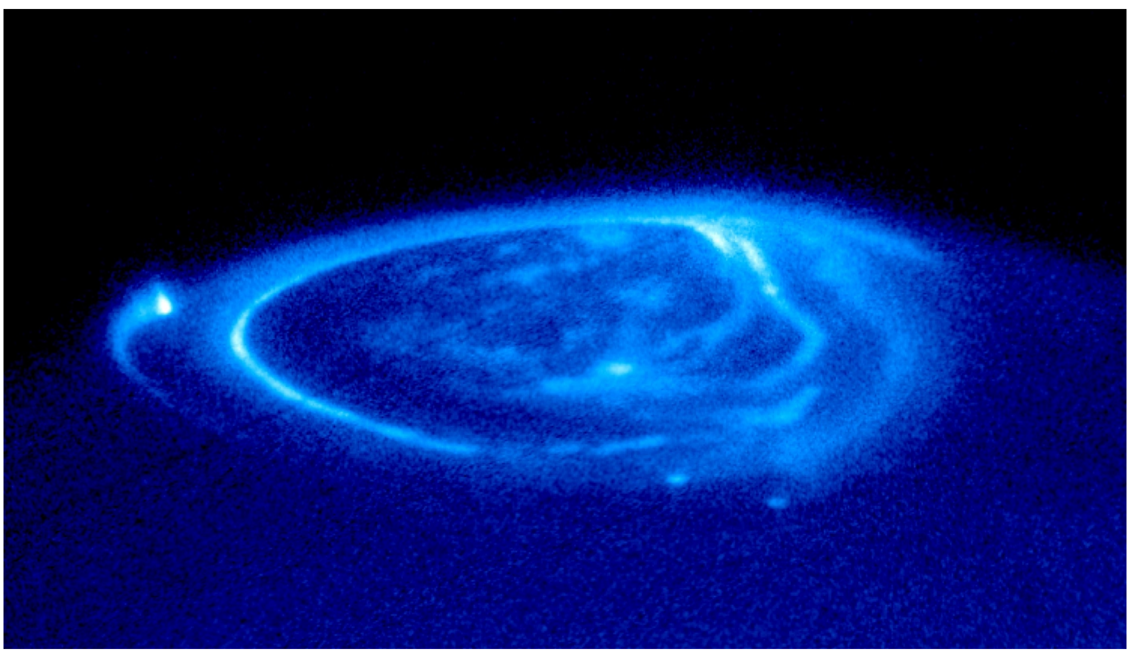

FIGURE 4.3 Jupiter's northern lights as seen in the ultraviolet by the Hubble Space Telescope. In addition to the auroral oval surrounding Jupiter's north magnetic pole, the "footprints" of three of the Galilean satellites are visible. Io's footprint is the prominent spot on the left, while those of Ganymede (near to the center) and Europa (to the lower right of Ganymede's) are less easily seen. (See Figure 4.4 for a schematic view showing the larger context for this image.) Courtesy of NASA/ESA and John Clarke, University of Michigan.

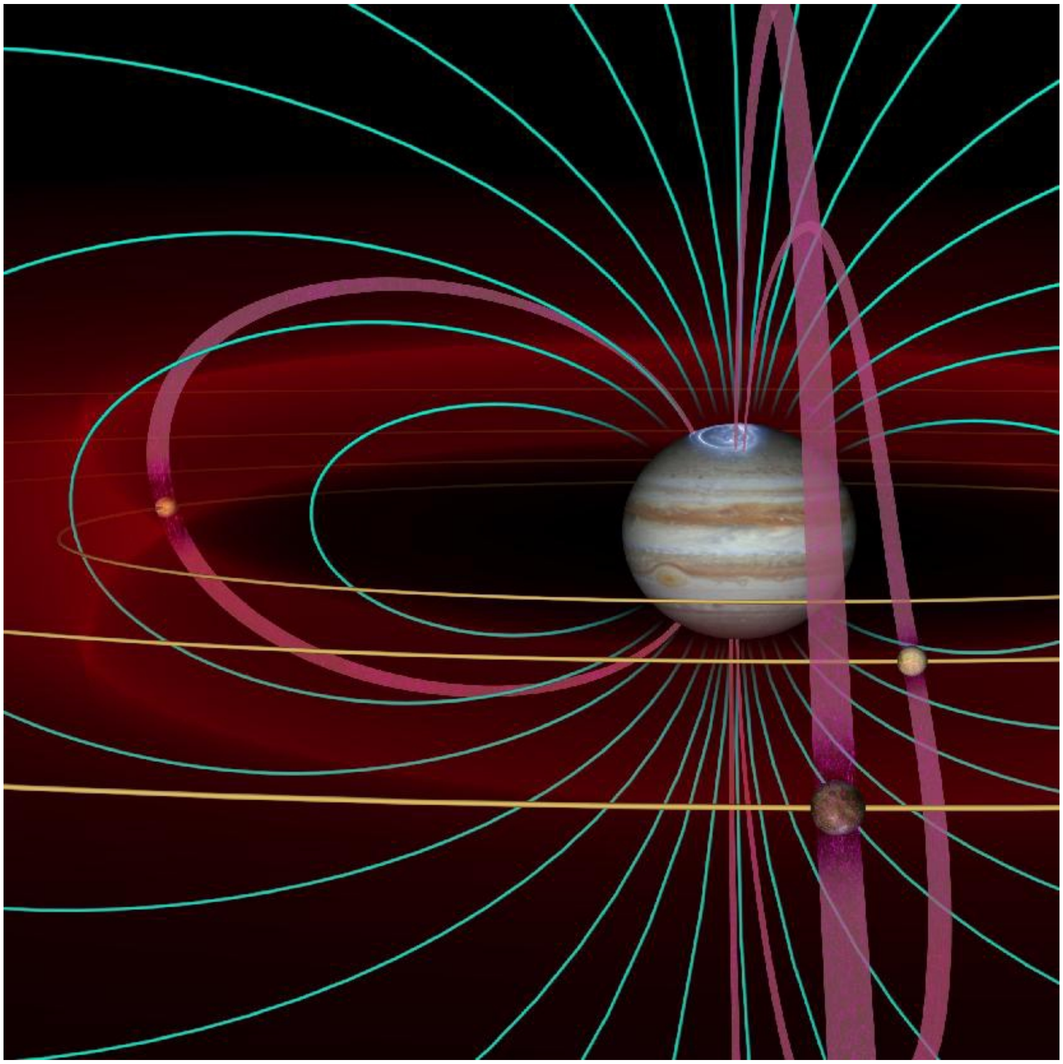

FIGURE 4.4 A schematic illustrating how three of Jupiter's Galilean satellites can leave their footprints on Jupiter's auroral emissions. Strong electric currents, flowing along magnetic flux tubes linking the satelites Io (*left*), Ganymede (*center*), and Europa (*right*) with Jupiter's northern and southern polar regions, stimulate ultraviolet emission in the planet's upper atmosphere. Courtesy of NASA/Boston University.

less dramatic than at Jupiter, is more easily distinguished from competing effects of dipole tilt, which produce a large noise signal at the spin period at Jupiter but are virtually absent at Saturn. Cassini observations at Saturn are thus a critical complement to those of Galileo at Jupiter.

Rotation is also a dominant factor in the magnetospheres of Uranus and Neptune, but with qualitatively new dynamics resulting from the extraordinarily large magnetic dipole tilt angles (59° and 47°, respectively) and offsets (0.3 and 0.55 planetary radii, respectively). The large dipole tilt angles, coupled with the large obliquities of the spin axes (98° and 29°, respectively), produce dramatic variations of the angle of attack between the solar wind and the planetary magnetic dipole.[32] The (acute) angle of attack spans all possible values (0° to 90°) at Uranus and a comparable range (14° to 90°) at Neptune during their orbits around the Sun. At certain favored orbital phases, even the diurnal variation spans a comparable range. For example, during the Voyager 2 encounter in 1989, Neptune's angle of attack varied between 66° (a rather Earth-like value) and 20° (a nearly pole-on geometry) in the course of one-half rotation of the planet. A nearly pole-on geometry (angle of attack <30°) will continue to occur diurnally at Neptune through the late 2020s and will next occur at Uranus during a decade-long window centered around 2014 (and again around 2042). The diurnal flip-flop of these vast magnetospheres between parallel and perpendicular configurations must produce qualitatively new dynamics, because it occurs on a time scale much shorter than the dynamical relaxation time scales of the systems.

The electric current circuit that transmits angular momentum from Jupiter to its distant magnetospheric plasma has many astrophysical analogs. For example, increasing astronomical evidence indicates that the mechanism that powers radio pulsars involves a similar electrodynamic coupling between a central rotating body and a surrounding disk. Solar system formation is a more obvious example. The angular momentum per unit mass of interstellar gas clouds is much greater than that of the solar system, so the system must have lost most of its angular momentum during formation. The outflowing solar wind could account for the loss, provided the gas was forced to corotate with the protosun out to large distances. This fundamental process can be studied in situ today within giant planet magnetospheres and most definitively by a polar-orbiting spacecraft at Jupiter.

Key Questions

Important questions about rings and plasma environments include the following.

Rings

- What are the current physical properties (size distribution, shapes, strength, and nature of aggregations) of particles in the various rings and of distinct regions within the rings?
- What are the most important mechanisms for ring evolution on long and short time scales?
- What are the underlying kinematics and dynamics of the various ring systems? How do self-gravity, viscosity, ballistic transport, and collisions interact?
- What is the chemical composition of the various rings and of distinct regions within the rings?
- What is the current mass flux into the various ring systems? What are the current size, mass, velocity, and composition distributions of the influx population? How did these change with time?
- What are the influences of the magnetospheric and plasma environments of the various rings?
- What do the differences among ring systems tell us about differences in ring progenitors and/or differences in initial and subsequent processes?
- What is the relationship between local ring properties and those properties observable by remote sensing?
- What do planetary rings teach us about nebulas around other stars?

Plasmas

- What is the nature of the electrodynamic coupling between major satellites and the ionospheres of their planets?
- How do the Io plasma torus and analogous structures at other planets convert planetary rotational energy into electromagnetic radiation over a wide range of frequencies?
- How are angular momentum transfer and other global magnetospheric processes revealed through auroral emission features?
- What is the spatial and temporal structure of centrifugally driven plasma transport in a rotation-dominated magnetosphere?
- How and where is the jovian planetary wind generated? Does Saturn have a planetary wind?
- How does the jovian pulsar work? Do other giant planets exhibit pulsar behavior?
- What role does electromagnetic angular momentum transfer, as observed in giant planet magnetospheres, have in solar system formation?

Future Directions

The Cassini mission, given a robust level of science support, is expected to revolutionize our knowledge of both the rings and the magnetosphere of Saturn. Phenomena discovered by Voyagers 1 and 2 in 1980 and 1981 will be explored in depth for the first time, and history tells us to expect the unexpected. For the study of rings and plasmas as for other areas of giant planet studies, our very first priority is to fully exploit the observational capabilities provided by the Cassini orbiter at Saturn.

Jupiter's magnetosphere, because it is the most powerful and the least Earth-like and because of its relative accessibility to both remote and in situ study, is the most promising target for extraterrestrial magnetospheric studies in the next decade. The Galileo mission, despite technical setbacks, filled important gaps in our observational knowledge of Jupiter's magnetospheric structure in the equatorial plane. However, as we have learned from the investigation of Earth's magnetosphere, extrapolations into the third dimension (away from the equatorial plane), in the absence of high-latitude observations, are suspect at best and embarrassingly wrong at worst. The next quantum jump in our understanding of Jupiter's magnetosphere depends on observations in the third (off-equatorial) dimension.

The most important directions for research on the rings and plasma environments of giant planets for the next decade are identified as follows:

- *Measuring the size distribution and composition of ring particles at various locations within the rings.* The Cassini spacecraft will make high-resolution measurements of Saturn's rings. For the ring systems of Jupiter, Uranus, and Neptune, ground-based spectra and stellar occultation data will be required. These measurements will aid in determining the origins and ages of the rings and of the various structures therein. A particle's composition reflects its evolutionary history, and its size determines its lifetime against sputtering and micrometeoroid erosion. Finding the larger bodies that are the likely source for dusty rings is an important objective.
- *Studying the relation among external satellites, embedded moonlets, and structures within the rings.* The observed structures within rings cannot be static, and the relative importance of different evolutionary mechanisms may itself evolve with time. Observations over long time periods are needed to characterize ring kinematics. Observed variations can be coupled with theoretical models to answer outstanding questions such as these: What is perturbing the orbit of Saturn's satellite Prometheus, and what is this satellite's relationship to the F ring? Can the presently observed frequency of meteoroid impacts explain the frequency of the short-lived spokes in Saturn's B ring? Are the Neptune ring arcs indeed confined in corotational resonances, or are they themselves transient?
- *Characterizing the electrodynamic coupling of Jupiter and Saturn with their satellites, rings, and plasma disks.* This is a complicated, three-dimensional puzzle that involves the global configuration of magnetic-field-aligned currents, the identity and velocity distribution of the charged particles that carry these currents, and the magnetospheric structures to which they connect. The solution of this puzzle requires measurements of charged particles, plasma waves, and vector magnetic fields at near-polar latitudes, preferably in conjunction with infrared and ultraviolet imaging of the planet and of its magnetospheric plasma.
- *Determining how internally produced plasma is ejected from a rotation-dominated magnetosphere.* We know that most of Jupiter's magnetospheric plasma comes from Io, deep in the heart of the magnetosphere, and is ultimately lost to interplanetary space in a planetary wind. We know very little of the intervening transport process. The nature of this process is critical to understanding not only the magnetospheres of Jupiter and Saturn but also a much larger class of astrophysical objects. Ordinary plasma particle and field measurements at low altitudes and high magnetic latitudes at Jupiter would revolutionize our understanding of this process.

KEY MEASUREMENT OBJECTIVES FOR GIANT PLANET EXPLORATION

Unanswered questions remain either because they pertain to depths below the reach of remote-sensing instruments or to regions of space close to the planet not penetrated by earlier spacecraft, or because they arose recently as a result of successful missions. New instruments mounted on new platforms and sent to new places will yield the answers. The following measurement objectives, listed in ranked order, have been identified for giant planet research. Jupiter, the prototypical gas giant, is the highest priority for a new mission. Neptune, the prototypical ice giant, is the next-highest priority.

First: Determine the Mass and Size of Jupiter's Core

One theory of giant planet formation says that a rock-ice "seed" of some 10 Earth masses is necessary to attract the lighter gases—hydrogen and helium. Another theory says that Jupiter-sized objects can form as stars do, attracting gas, ice, and dust directly from the nebula. The latter process produces an object without a core. The two scenarios have vastly different consequences for giant planet and solar system formation. The core manifests itself both in the rotational bulge, which is the response of the planet to its own rotation, and in the tidal bulge, which is the response of the planet to the gravitational pull of the satellites. Both bulges have signatures in the planet's gravity field, which can be measured from an inclined orbit with periapse close to the planet. An independent technique uses distortions of the magnetic field near the pole to infer the core's radius, in analogy with Earth's magnetic field, which reveals the inner core's radius.[33] A low-periapse polar-orbiting spacecraft equipped with a radio transponder and vector magnetometer is required.

Second: Measure Elemental Abundances (H, He, O, C, N, S)

The water abundance (hence, the O/H ratio) in Jupiter's atmosphere is uncertain by an order of magnitude, even though oxygen is expected to be the third-most-abundant element after hydrogen and helium. Water plays an important role in giant planet formation. The O/H ratio tells us how giant planets got their volatiles (H_2O, CH_4, NH_3, and H_2S) and, in particular, the extent to which the volatiles were carried in from beyond Neptune's orbit to the inner solar system on icy planetesimals. Water is also important to the meteorology of giant planets, as it is on Earth. The Galileo probe penetrated below the jovian clouds, but the composition was still varying when the probe reached its maximum depth at 24 bars. The fact that the probe entered an unusually hot, dry region hindered the interpretation. Better coverage in latitude and penetration to greater depth are needed. This need can be met with the following two complementary approaches.

- *Multiple entry probes carrying mass spectrometers.* A dedicated spacecraft should be able to carry three probes that enter within 30 degrees of the equator and reach depths of 100 bars. The carrier makes a polar pass where it collects the data from each probe, and then transmits to Earth. Having only three probes is a limitation, but it is sufficient to resolve the ambiguity left by the single Galileo probe. Ammonia is measured separately by monitoring the attenuation of the probe's radio signal (measuring ammonia by mass spectrometry is not accurate because it coats the walls of the chamber).
- *Microwave radiometry.* This technique uses thermal emission from the planet at wavelengths between 10 and 100 cm to measure the water and ammonia abundance from 10 to hundreds of bars. To avoid interference from Jupiter's radiation belts, the measurement must be made when the spacecraft is less than several thousand kilometers above the tops of the clouds. A polar-orbiting spacecraft is best because it gives latitude and longitude coverage while avoiding radiation-belt and ring-particle hazards. Interpretation of the radiometry results is facilitated by knowledge of the temperature profile, which can be measured by an entry probe. Multiprobes provide ground-truth for interpreting the radiometer observations, which in turn provide global coverage that is not obtainable from a limited number of probes.

Third: Investigate Deep Winds and Internal Convection

Jupiter's jet streams and oval storms may get their 100-year longevity from massive jet streams and convection cells in Jupiter's interior. The degree of coupling between motions in the visible atmosphere and the interior depends on the thermal structure, which itself is unknown. A probe can measure both thermal structure and winds, the latter using the Doppler shift in the probe's radio signal. A probe can also measure clouds, sunlight, and gaseous composition, but only to depths of 100 bars, at least for Jupiter. Motions at deeper levels may be inferred from the planet's gravity field. For instance, if the observed jet streams extend down to kilobar pressures, the gravity field will look noticeably "rougher" than if the interior is in solid body rotation.[34]

An orbiting spacecraft that skims close to the top of the atmosphere can measure this fine structure of the gravity field. It could also measure the fine structure of the magnetic field, which might tell us if the winds extend to the depth where the fluid becomes an electrical conductor: The tilted dipole field appears to be time-dependent in the reference frame of the moving fluid, and the time-dependence produces electrical currents that cause observable changes in the field.[35]

Fourth: Map the Structure of Magnetic Field

The goal is to understand how planetary dynamos operate. Previous spacecraft did not spend enough time close to Jupiter or any of the other giant planets to measure the fine structure and temporal variations of the magnetic field. The external field can be extrapolated down to the level where the fluid becomes an electrical conductor. At Earth this level is the liquid iron core, and there the spectrum of the magnetic field is flat—the different harmonic components of the field all have comparable amplitudes. This may be a fundamental property of planetary dynamos. The fields of the giant planets provide an opportunity to find out.

Fifth: Explore Polar Magnetospheres

The solar wind, the satellites, the rings, and the planet can all act both as sources and as sinks of charged particles that populate the magnetosphere. The polar regions, where magnetospheric particles interact with the planetary atmosphere to produce the aurora and related radio emissions, are particularly important. There, magnetic field lines from the distant magnetosphere and from interplanetary space reach the planet's atmosphere. Previous spacecraft missions to the giant planets have not explored the auroral zone because they were designed to visit satellites in the equatorial plane and to avoid radiation and ring particle hazards close to the planet. However, a polar orbiter with a near-equatorial periapse just above the cloud tops will traverse the polar region at a distance of 2 to 3 planetary radii from the planet's center, while avoiding the rings and most of the radiation belts (Figure 4.5). Existing instruments can sample the composition, density, and velocity distribution of the charged particles and learn where they come from. Jupiter is interesting because it has the largest and most powerful magnetosphere and because our knowledge of it is largely restricted to the equatorial plane. Neptune is interesting because the tilt of the field exposes the polar cusp to the solar wind on every rotation. This 16-hour periodicity allows one to see the sources and sinks in operation on very short time scales. A Neptune orbiter that reaches high latitudes could take advantage of this opportunity.

Sixth: Determine the Properties of Planetary Rings

Composition, particle size, number density, collisional efficiency, and collective behavior are some of the most important properties of planetary rings. The Cassini orbiter has the potential to do an exquisite job with the most massive rings in the solar system. A Cassini extended mission would provide data on decadal changes, including thermal effects when the rings are edge-on to the Sun, dynamical effects when nearby satellites pass in their orbits, and secular changes brought about by collisions with interplanetary bodies. However, celestial mechanics prevents Cassini from hovering over the rings. Such hovering would allow one to follow individual ring particles as they collide with each other, but technological developments are needed to accomplish this.

Seventh: Map Atmospheric Properties as Functions of Depth, Latitude, and Longitude

The Cassini mission will provide a wealth of new information about the three-dimensional structure of Saturn's atmosphere. However, Earth-based telescopic observations are an essential complement to in situ studies at Jupiter and Saturn and are the only source of such information for Uranus and Neptune in the next decade. Three-dimensional distributions of atmospheric composition, temperature, aerosols, winds, and auroral emissions

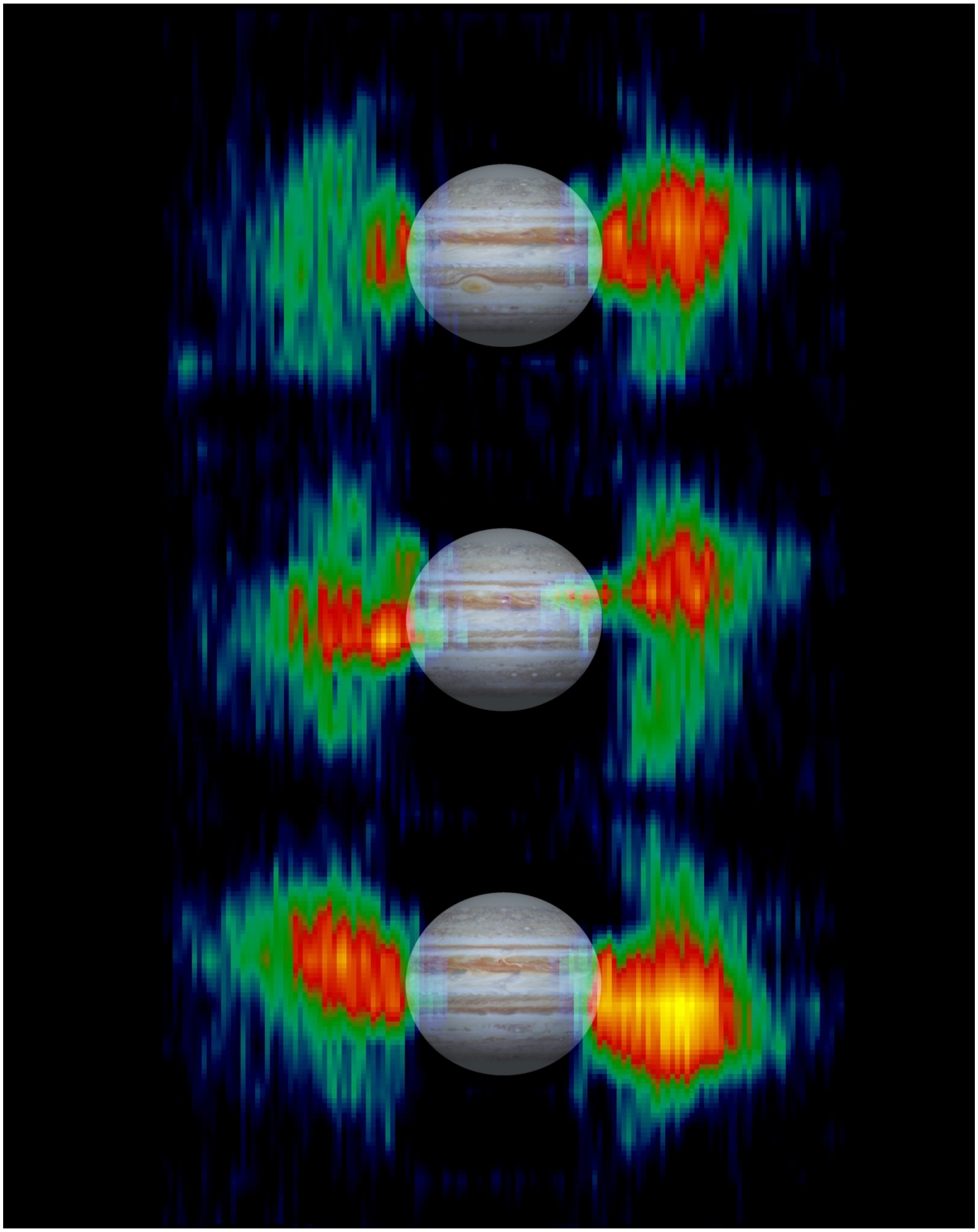

FIGURE 4.5 Cassini's radar system doubled as a radio telescope to collect these images showing the variations in Jupiter's trapped radiation belts over a 10-hour period. The radio emission has a wavelength of 2.2 cm and originates from electrons trapped in Jupiter's intense magnetic field. The belts wobble with respect to the superposed optical images because Jupiter's magnetic axis is inclined with respect to its rotation axis. Courtesy of NASA/JPL.

are poorly known for the outer planets. This situation can be improved dramatically in the next decade by utilizing large ground-based telescopes with adaptive optics, advanced detectors, and the expanded wavelength coverage available from space-based telescopes.

SPACE MISSIONS FOR GIANT PLANET EXPLORATION

Space Missions

The Cassini orbiter is scheduled to begin its exploration of the Saturn system in late 2004. The success of this historic effort is a matter of the highest scientific priority, and it should also be a matter of the highest programmatic importance.

The Giant Planets Panel has identified a single medium-class new mission that addresses most of the key questions described above for a gas giant—a Jupiter polar orbiter with three atmospheric entry probes. This mission requires only incremental technological development. It can and should be launched in this decade. For the longer term, the panel has identified a single large-class mission that addresses most of the key questions for an ice giant—a Neptune orbiter with multiple entry probes. The Neptune mission, among others, requires new technology development that should be initiated in this decade to enable consideration in the following decade. Table 4.1 summarizes how these missions and other activities address the key science questions discussed above.

Jupiter Polar Orbiter with Probes

The Jupiter Polar Orbiter with Probes (JPOP) mission combines several smaller missions that have recently been proposed or studied by NASA teams. Combining them as one mission reduces transportation costs and enhances the science return, because the measurements complement each other in important ways. The elements of the mission are as follows:

- A polar orbiter (periapse <1.1 R_J) spacecraft for atmospheric remote sensing, gravity analysis, particles and fields measurements, and probe data relay; and
- Three atmospheric probes that can penetrate to the 100-bar pressure level and that can sample a range of latitudes within 30 degrees of the equator for atmospheric sounding.

JPOP carries a microwave radiometer that is used for remote sensing of atmospheric composition when it is inside the radiation belts; thus, the periapse of the orbiter must be close to the planet. The polar inclination and low periapse are also essential to avoid radiation and ring hazards. The radiometer obtains estimates of the water and ammonia abundances to depths of hundreds of bars. The pole-to-pole coverage complements the mass spectrometers on the probes, which sample a range of latitudes within ±30 degrees. The mass spectrometers on the probes provide ground-truth for the microwave radiometer. The probes measure composition, winds, temperatures, clouds, and sunlight as functions of pressure to 100 bars.

After dropping off the probes and relaying their signals to Earth, JPOP spends a year or more in a highly inclined orbit with periapse near the equatorial plane <1.1 R_J from the planet center. It measures the magnetic field, charged particles, and plasma waves close to the planet. Radio occultations probe the atmospheric dynamical structure. The orbit itself is sensitive to the fine structure of the gravity field. Both the axisymmetric part due to Jupiter's internal mass distribution and the nonaxisymmetric part due to satellite-induced tides are measured. The microwave radiometer, away from periapse, provides the first three-dimensional map of Jupiter's radiation belts. Additional remote sensing (ultraviolet, visible, infrared) would be desirable but is not critical to the success of the mission.

Cassini—Nominal Mission

The performance of the Cassini spacecraft and instruments during the December 2000 Jupiter flyby bodes well for the potential success of the Cassini orbiter mission at Saturn. To realize this potential, hard decisions have to be made concerning science priorities. Past economies and added taxes have affected the run-out costs of this program, threatening the community's ability to ingest and interpret the data. As the mission progresses and the capabilities of the instrument complement are known, the run-out budget should be enhanced to allow optimal analysis by team members and the larger science community.

Cassini—Extended Mission

After the nominal Cassini mission ends, coverage of many parts of the Saturn system, including Titan's surface and the polar regions of the planet and its magnetosphere, will be incomplete. A Cassini extended mission should be formulated and priced in order to obtain optimal science-to-cost ratio. The Cassini Saturn science complements that from the proposed Jupiter Polar Orbiter with Probes mission. Critical choices should be made to optimize the total yield from these missions.

Neptune Orbiter with Probes

The objectives of this longer-term mission span the planet, rings, magnetosphere, and satellites, particularly Triton. The spacecraft would carry remote-sensing instruments as well as instruments to sample particles and fields. Compared with the Jupiter Polar Orbiter with Probes, the Neptune mission would be more comprehensive, as befits a planet about which less is known. Trade-offs would have to be made among the orbit, payload, power, telemetry, and other resources. Satellite objectives are described in other chapters. Here the panel describes objectives arising from the planet, the rings, and the magnetosphere.

As with Jupiter, knowing the volatile abundances has high priority. The cloud base for water may be deep within the planet, so the atmospheric abundance might reflect the saturation vapor pressure rather that the bulk water abundance of the interior. Other volatiles such as CH_4, NH_3, and H_2S may have cloud bases within the range of probes and microwave remote-sensing observations, so it would be possible to sample the well-mixed planetary interior for these compounds. Both the gravity field and magnetic field are of great interest. Voyager showed that the magnetic field is "rougher" than that of Jupiter or Saturn, suggesting that the dynamo region is closer to the surface. Low periapse altitude, at least on some of the orbits, is highly desirable. Comprehensive sampling of the magnetosphere in latitude, longitude, altitude, and local time has high priority. Neptune offers a unique opportunity to study the interaction of the magnetosphere with the solar wind on diurnal time scales.

Within the neptunian rings, the vertical and radial structure is poorly defined and the composition is undetermined. More than any other ring system, Neptune's rings illustrate close dynamical associations between dusty rings and a set of small, embedded satellites. The surfaces of the inner ring-region satellites, orbiting within the Roche zone, should record the stresses they have undergone. This is especially true for Galatea, the satellite responsible for confinement of the ring arcs. Bringing the understanding of the neptunian ring system up to a level similar to that of the Saturn and jovian rings will allow comparative ring studies to better understand why the ring systems differ.

Enabling technologies for a Neptune Orbiter with Probes mission (see below) include nuclear electric propulsion and power sources, enhanced telemetry, improved heat shields, lightweight instruments for entry probes, and possibly aerocapture.

TABLE 4.1 Relationships of Recommended Initiatives to Key Science Questions for Giant Planet Exploration

		Mission								
Class of Question	Scientific Themes	Jupiter Polar Orbiter with Probes	Cassini Nominal Mission	Cassini Extended Mission	Earth-Based Orbiting Facilities	Neptune Polar Orbiter with Probes	Saturn Ring Observer	Uranus Orbiter with Probes	Analysis and Modeling	Laboratory
Theme 1. ORIGIN AND EVOLUTION										
Solar-System Giant Planets										
Paradigm altering	How did the giant planets form?	xxx	xx	xxx	x	xxx	x	xxx	xx	xx
Paradigm altering	What are the orbital evolutionary paths of giant planets?	xxx	xx	xxx	o	xxx	xx	xxx	xxx	o
Pivotal	Does Jupiter have a rock-ice core?	xxx	o	o	o	o	o	o	xx	x
Pivotal	What are the elemental compositions of the giant planets?	xxx	xx	xx	x	xxx	o	xxx	xx	x
Pivotal	What are the internal structures and dynamics of giant planets?	xxx	xx	xxx	xx(1)	xxx	o	xxx	xx	xx
Extrasolar Giant Planets and Brown Dwarfs										
Pivotal	How can we use the giant planets in our solar system to calibrate spectroscopic observations (optical, infrared, radio) of extrasolar giant planets?	xxx	xx	xx	xx	xxx	o	xxx	xxx	x
Foundation building	Around what types of stars do we find giant planets?	AP	AP	AP	AP	AP	AP	AP	AP	o
Foundation building	Are multiple giant planets common in stellar systems?	AP	AP	AP	AP	AP	AP	AP	AP	o
Foundation building	In what ways do giant planets differ from brown dwarfs?	AP	AP	AP	AP	AP	AP	AP	AP	o
Foundation building	What are the properties of extrasolar giant planets (radii, effective temperatures, compositions, clouds, moons, winds, magnetic fields, heat flows)?	AP	AP	AP	AP	AP	AP	AP	AP	o
Theme 2. INTERIORS AND ATMOSPHERES										
Interiors										
Pivotal	What is the nature of phase transitions within the giant planets?	xxx	xx	xxx	xx(1)	xxx	o	xxx	xx	x
Pivotal	How is energy transported through the deep atmosphere? Do radiative layers exist?	xxx	xx	xx	xx(1)	xxx	o	xxx	xx	x
Pivotal	How and where are planetary magnetic fields generated?	xxx	xx	xx(2)	x(1)	xxx	o	xxx	xxx	o
Foundation building	What is the nature of convection in giant planet interiors?	xxx	xx	xx(2)	xx(1)	xxx	o	xxx	xxx	o
Foundation building	How does the composition vary with depth?	xxx	xx	xx(2)	x(1)	xxx	o	xxx	xx	o

Atmospheres										
Pivotal	What energy source maintains the zonal winds, and how do they vary with depth? What role does water and moist convection play?	xxx	xx	xx	x	xxx	o	xxx	xx	x
Pivotal	What physical and chemical processes control the atmospheric composition and the formation of clouds and haze layers?	xxx	x	x	x	xxx	o	xxx	xx	x
Foundation building	How and why does atmospheric temperature vary with depth, latitude, and longitude?	xxx	xx	xx	x	xxx	o	xxx	xx	x
Foundation building	How does the aurora affect the global composition, temperature, and haze formation?	x	xx	xx	x	x	o	x	xx	x
Foundation building	What produces the intricate vertical structure of giant planet ionospheres?	xx	xx	xx	x	xx	o	xx	xx	x
Foundation building	At what rate does external material enter giant planet atmospheres, and where does this material come from?	o	x	x	x	o	o	o	xx	x
Foundation building	What can organic chemistry in giant planet atmospheres tell us about the atmosphere of early Earth and the origin of life?	x	x	x	x	x	o	x	xx	x
Theme 3. RINGS AND PLASMAS										
Rings										
Paradigm altering	What are the most important mechanisms for ring evolution on long and short time scales? How do self-gravity, viscosity, ballistic transport, and collisions interact?	o	xx	xxx	x	xxx	xxx	xxx	xxx	x
Pivotal	What do planetary rings teach us about nebulas around other stars?	AP	AP	AP	AP	AP	AP	AP	AP	AP
Foundation building	What are the present physical properties (composition, size distribution, shapes) of particles in the various distinct regions within the various rings?	o	xxx	xxx	x	xxx	xxx	xxx	xx	xx
Foundation building	What is the present mass flux into the various ring systems? What are the present size, mass, velocity, and composition distributions of the influx population?	o	xx	xx	o	xx	xx	xx	x	o
Foundation building	What is the relationship between local ring properties and those properties observable by remote sensing?	o	xxx	xx	xx	xx	xxx	xx	xx	x
Foundation building	How fast are angular momentum and energy being transferred among rings and moons?	o	xx	xx	x	xx	xxx	xx	xx	o
Foundation building	What is the influence of magnetospheric plasma on the rings?	o	xx	xx	o	xx	xxx	xx	x	o
Plasmas										
Paradigm altering	What is the nature of the electrodynamic coupling between major satellites and the ionospheres of their planets?	xxx	xxx	xx	x	xx	o	xx	xx	o
Pivotal	What is the spatial and temporal structure of centrifugally driven plasma transport in a rotation-dominated magnetosphere?	xxx	xx	xx	o	x	o	x	xx	o
Pivotal	What role does electromagnetic angular momentum transfer, as observed in giant planet magnetospheres, have in solar system formation?	AP	AP	AP	o	AP	o	AP	AP	o
Foundation building	How do the Io plasma torus and analogous structures at other planets convert planetary rotational energy into electromagnetic radiation over a wide range of frequencies?	xx	xx	x	x	x	o	x	xx	o
Foundation building	How are angular-momentum transfer and other global magnetospheric processes revealed through auroral emission features?	xxx	xx	xx	o	x	o	x	xx	o
Foundation building	How and where is the jovian planetary wind generated? Does Saturn have a planetary wind?	x	xxx	xx	o	o	o	o	xx	o
Foundation building	How does the jovian pulsar work? Do other giant planets exhibit pulsar behavior?	xxx	xxx	xx	x	x	o	x	xx	o

NOTE: o, not applicable; x, significant advance in understanding; xx, major advance; xxx, breakthrough; AP, results relevant to NASA's Astronomical Search for Origins program; (1), assumes P-modes will be detected; and (2), assumes high-inclination orbits.

Other Mission Concepts

Two other promising concepts for longer-term missions are listed here, without any ranking. As is the Neptune Orbiter with Probes, they are dependent on the development of enabling technologies.

Saturn Ring Observer

On a Saturn Ring Observer mission, advanced propulsion would be used to hover close above the ring plane for long-term study of collisions and other microphysical processes.

Uranus Orbiter with Probes

The science objectives and payload of a Uranus Orbiter with Probes mission would be similar to those of the Neptune Orbiter with Probes mission.

Key Enabling Technologies and Earth-Based Facilities for Giant Planet Exploration

Technology Development

Two incremental technological developments are needed for atmospheric probes to the 100-bar pressure level at Jupiter during the present decade:

- Lightweight heat shields, and
- Lightweight (a few kilograms) mass spectrometers.

To enable high-priority missions in later decades, the following technological goals need to be pursued vigorously in the present decade:

- Implement nuclear-electric propulsion;
- Obtain enhanced telecommunications, including large microwave arrays and/or optimization of the NASA's Deep Space Network (DSN); and
- Determine the feasibility of implementing aerocapture in giant planet atmospheres.

In addition, outer-planet missions require nuclear-electric power sources such as radioisotope power systems (RPSs). Although the technology is well in hand, procurement steps must be taken to ensure availability.

Earth-Based Facilities

Important Earth-based facilities include large ground-based telescopes, survey telescopes, space telescopes, and large radio arrays. All of these have general astronomical applications. The study of giant planets around other stars is a booming and important field, which will rely increasingly on solar system giant planets for calibration. Here the panel emphasizes what can be learned about our own giant planets from these Earth-based facilities.

Giant (20- to 30-m) Segmented Mirror Telescope

The adaptive optics (AO) capability will provide diffraction-limited imaging of solar system objects. The large light-gathering power of the telescope allows high-resolution spectroscopy of the outer planets, which is critical for determining altitude variations of their atmospheric properties. The planetary community needs to help define the capabilities of the AO system and the specific instruments that will be developed for this telescope. The ability to track moving targets is important for solar system studies in general.

Dedicated Planetary Telescope and/or Refurbished IRTF

Some areas of planetary science are best served by long-term monitoring. Examples include dynamic features in giant planet atmospheres, the jovian magnetosphere and its response to volcanic outbursts from Io, and spacecraft missions that need Earth-based support. These activities need large blocks of observing time. The solution is to have a dedicated planetary telescope such as NASA's Infrared Telescope Facility (IRTF), although that telescope needs refurbishment to keep up with modern demands and to utilize modern technology.

Space Telescopes

Although ground-based telescopes with AO systems can surpass the diffraction-limited imaging capabilities of space-based telescopes, the latter allow one to observe in the ultraviolet and far infrared where ground-based telescopes cannot. Space-based telescopes also have a more nearly continuous duty cycle. Planetary scientists must be included in early planning and development to ensure that space telescopes have instruments and tracking capabilities that serve solar system research objectives.

Square-Kilometer Array

The Square-Kilometer Array (SKA) is a proposed international radio astronomy venture that parallels enhancements that are being discussed for the Deep Space Network. The DSN is primarily for telemetry and the SKA is primarily for listening, but it would be desirable if the two arrays were compatible and could be arrayed together for special events and unusual scientific opportunities.

RECOMMENDATIONS OF THE GIANT PLANETS PANEL TO THE STEERING GROUP

The study of giant planets stands at the threshold of a new era. Even as we complete the first systematic explorations of Jupiter and Saturn with orbiting spacecraft, we are witnessing an explosion in the number of known giant planets around other stars. As we struggle to comprehend the diversity of planetary systems discovered elsewhere in our galaxy, we are reminded of certain fundamental things that we do not yet know about our own impressive system of four giant planets. For example, we do not know if Jupiter has a solid core, or if it contains enough water to support standard theories of solar system formation and evolution. We do not fully understand the mechanism that produces and sustains the banded atmospheric structure or how deep that structure goes, or how it might affect the distant spectral signature of a giant planet under the most general range of possible conditions. We are just beginning to probe the complexities of the many-body gravitational interactions that shape the rings, and the magnetohydrodynamic interactions that shape the magnetospheres, although both are likely to be important during the course of stellar and planetary evolution. On the other hand, we know far more than we did two decades ago. The legacy of the Voyager, Galileo, and (soon) Cassini missions and concurrent ground-based work is that we now know how to formulate the questions presented above in a precise manner, and indeed, we know how to find the answers.

As far as we know, there are two generic types of giant planet—the gas giants like Jupiter and Saturn and the ice giants like Uranus and Neptune. A better understanding of the nature of both types is needed, both to answer fundamental questions concerning the formation of the solar system and to guide the interpretation of observations of other planetary systems.

In assigning priorities for future missions to the giant planets, a variety of factors must be and have been considered. Long travel times and tight mass and communication constraints are a given with missions to the outer planets. The need for near-term development of enabling technologies for longer-term missions must be considered. Above all, it must be recognized that extrasolar planets will increasingly become a focus of both scientific and popular attention, as evidenced by the selection of Kepler—a Discovery mission designed to search for extrasolar planets by looking for the luminosity variations they may cause as they transit the disks of their parent stars. Many more extrasolar planets will be detected in the next decade. Some will be imaged, and their spectra will be partially resolved. To provide critical ground-truth for these exciting discoveries, NASA should pursue a parallel program of close-up exploration and analysis of our own giant planets. These two lines of investigation can be, and should be, synergistic.

For the next decade, the Giant Planets Panel recommends the following initiatives, in ranked order:

1. *Characterize the gas giant Jupiter.* The centerpiece of this effort should be a dedicated mission such as the polar orbiter with three entry probes described above. Earth-based observational and theoretical efforts would, as always, be essential complements to this spacecraft mission. The mission is scientifically focused and technologically feasible with only modest improvements to available technology. It addresses several outstanding questions that are fundamental both for understanding the solar system and for calibrating observations of other planetary systems.

2. *Exploit the capabilities of the Cassini orbiter at Saturn.* Every effort should be made to maximize the scientific yield from the Cassini orbiter mission. As the mission progresses, the quality of the data should be assessed and the level of science support within the instrument teams should be enhanced accordingly. Funding should be provided to the research community for data analysis, and a plan for extending the primary mission should be developed on the basis of new science that can be achieved.

3. *Enhance the productivity of Earth-based studies.* Many of our key questions can be addressed effectively with Earth-orbiting telescopes and ground-based telescopes utilizing adaptive optics. Planetary scientists should be actively engaged in defining the capabilities and scheduling of these advanced observing platforms. Some questions require a dedicated telescope for systematic long-term monitoring. The maintenance and refurbishing of the IRTF for this purpose is a continuing priority. Maximizing the science return from both in situ and Earth-based observations requires a robust concurrent program of data analysis and modeling efforts.

4. *Prepare for future exploration of the ice giant Neptune.* Preparations must begin in this decade to enable a future mission to Neptune, as described above. Technology needs for such a mission include nuclear-electric propulsion and advanced power sources, enhanced telecommunications, and lightweight (a few kilograms) mass spectrometers and heat shields for entry probes.

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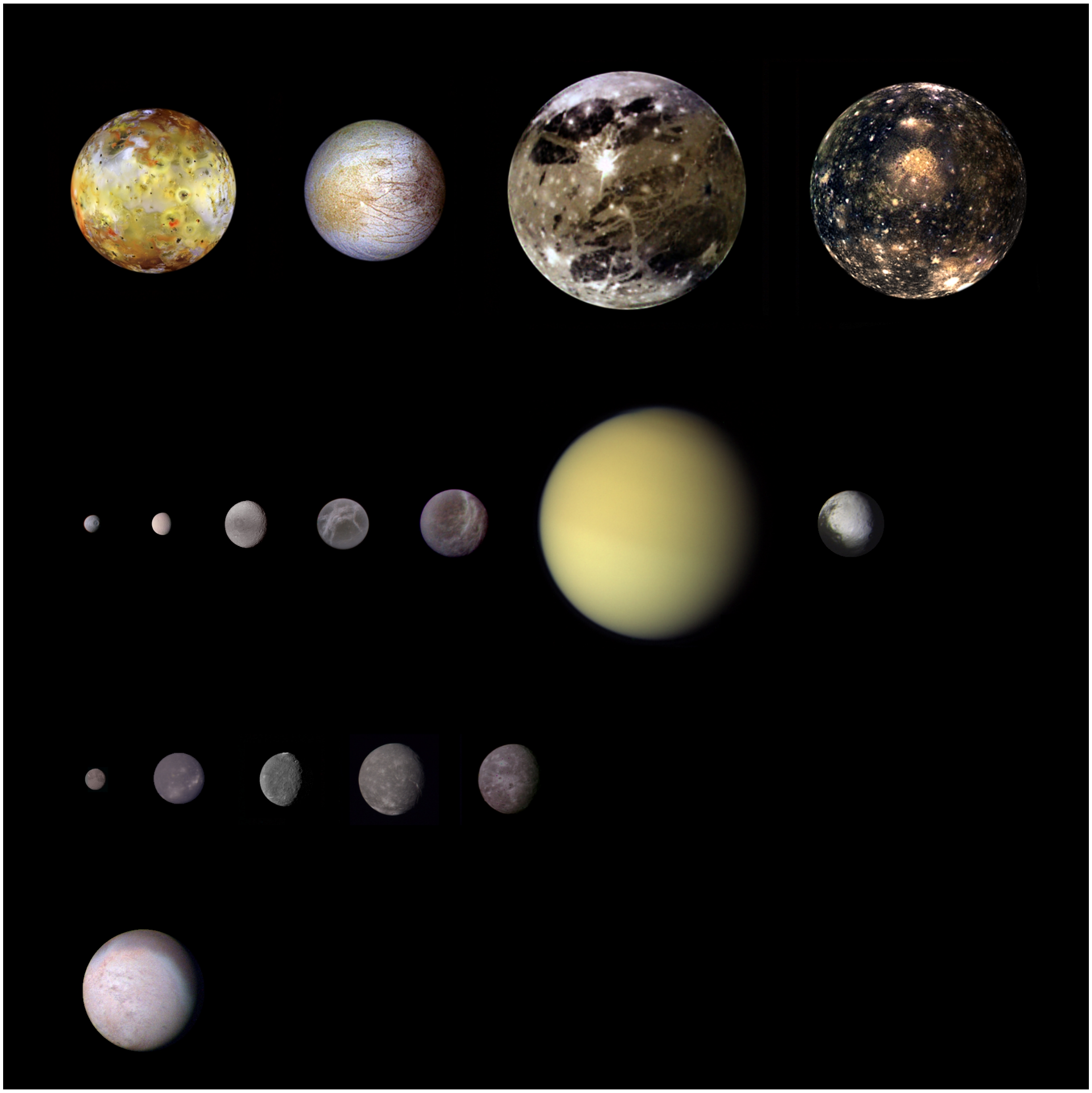

5

Large Satellites: Active Worlds and Extreme Environments

Of the six large outer-planet satellites—Io, Europa, Ganymede, Callisto, Titan, and Triton—all are larger than Pluto and two are larger than Mercury; in addition, there are 11 medium-sized satellites (Figure 5.1; Table 5.1). Each planet-sized satellite is unique:

- Io is intensely volcanically active,
- Europa may have a layer of subsurface water greater in volume than all of Earth's oceans combined,
- Ganymede has an intrinsic magnetic field,
- Callisto is largely undifferentiated,
- Titan has a thick atmosphere rich in organic compounds, and
- Triton has active, geyserlike eruptions.

The large satellites have bizarre life cycles, influenced by orbital evolution and tidal heating, revolutionizing concepts based on the terrestrial planets. They are rich in volatile species such as H_2O, SO_2, N_2, CH_4, CO_2, and perhaps NH_3, creating a rich diversity of processes and environments. The 11 medium-sized satellites are also unique worlds, and they may provide essential information about the origin and evolution of satellite systems.

FIGURE 5.1 *(facing page)* The 17 large and medium-size satellites of the outer planets, shown to scale, are worlds in their own right. The Galilean satellites of Jupiter (*top row*) are (*from left*) Io, whose surface is constantly renewed by active volcanoes tinged with sulfur allotropes; Europa, which probably possesses a liquid water ocean beneath its ruddy ice skin; Ganymede, a moon bigger than the planet Mercury, possessing a rutted surface of dirty ice and an internally generated magnetic field; and Callisto, a moon with an ancient cratered surface whose interior is only weakly differentiated. Saturn's family of bright icy moons (*second row*) consists of Mimas, Enceladus, Tethys, Dione, and Rhea; cloud-shrouded Titan has an atmosphere rich in organics and possibly seas of methane; and two-toned Iapetus shows one face as bright as snow and the other as black as coal. The five major uranian satellites (*third row*) are Miranda, Ariel, Umbriel, Titania, and Oberon. Each displays a dirty-ice surface and some tectonic activity, but the bizarre world of Miranda—with its exotic jumble of surface terrains suggesting that it may have been totally disrupted in the past and put back together at random—steals the show. Neptune's sole large satellite (*fourth row*), Triton, is coated with exotic ices tinged pink by organic molecules; nitrogen geysers spew high into its tenuous atmosphere. Courtesy of NASA/JPL.

TABLE 5.1 Large- and Medium-Sized Satellites of the Outer Solar System

Planet	Satellite	Semimajor Axis (10^3 km)	Rotation Period (days)	Diameter (km)	Mass (10^{20} kg)	Density (kg/m^3)
Jupiter	Io	422	1.77	3,643	893	3,500
	Europa	671	3.55	3,120	480	3,000
	Ganymede	1,070	7.15	5,276	1,482	1,900
	Callisto	1,883	16.69	4,820	1,076	1,800
Saturn	Mimas	186	0.94	394	0.375	1,200
	Enceladus	238	1.37	502	0.7	1,100
	Tethys	295	1.89	1,048	6.27	1,000
	Dione	377	2.74	1,120	11.0	1,500
	Rhea	527	4.52	1,528	23.1	1,200
	Titan	1,222	15.95	5,150	1,346	1,900
	Iapetus	3,561	79.33	1,435	16	1,000
Uranus	Miranda	129	1.41	472	0.66	1,200
	Ariel	191	2.52	1,158	13.5	1,700
	Umbriel	266	4.14	1,169	11.7	1,400
	Titania	436	8.71	1,578	35.3	1,700
	Oberon	584	13.46	1,523	30.1	1,600
Neptune	Triton	355	5.88	2,705	214	2,100

WHY DO WE CARE ABOUT LARGE SATELLITES?

Why are these large satellites worthy of national and international exploration and research? One good reason is that advancing basic research about physical processes in fields such as volcanology and meteorology may eventually provide benefits that will improve our lives. Another is that such interesting worlds inspire our youth and students to excel in mathematics and science. But the most compelling motivation is to understand the origin and destiny of life. Water is essential to life as we know it, and the large icy satellites may contain the largest reservoirs of liquid water in the solar system. Outside Earth, Europa may be the best place in the solar system to search for extant life. Titan provides a natural laboratory for the study of organic chemistry over temporal and spatial scales unattainable in terrestrial laboratories. Perhaps teeming with life or perhaps sterile today, these worlds do contain the basic ingredients for life. Knowing whether they do or do not harbor life is equally important. The origin and evolution of satellite systems also provide analogs for understanding extrasolar planetary and satellite systems, some of which may be abodes for life.

Origins and Orbital Dynamics

The accretion process that led to the formation of the solar system also led to the formation of satellite systems around the giant planets. The results of four additional accretion "experiments" within the solar system are therefore available for detailed study. The fundamental process of accretion leading to the formation of satellite systems is directly analogous to that leading to the planets, but other processes—for example, gas drag and tidal interactions—may have had more or less important roles in the protoplanetary nebulae. Since the satellites are much too small to capture hydrogen or helium, they provide a record of the inventory of condensable species in the protoplanetary nebulae. The size, distribution, and compositions of the satellites within a system also inform us about the physical and dynamical conditions during accretion. The Galilean satellites, for example, apparently contain a record of the temperature gradient in the nebula in which they formed through their decreasing density with distance from Jupiter (see Table 5.1). Such a trend is not obvious in the other satellite systems. The formation of four large satellites in the jovian system while other systems have at most one is perhaps indicative of a denser nebula around the young Jupiter.

The periodic driving forces of orbital resonances have played an important role in the formation of planetary and satellite systems. This is evident in the dynamics of the outer-planet satellites, many of which are currently involved in orbital resonances. The importance of tidal dissipation in the origin and evolution of resonant configurations is apparent in the jovian system, where Io, Europa, and Ganymede interact through multiple resonances, and where tidal dissipation drives Io's volcanism and may maintain an ocean within Europa. At Saturn, resonances currently exist between the satellite pairs Mimas-Tethys, Enceladus-Dione, and Titan-Hyperion; and at Uranus, paired resonances likely once existed among the satellites Miranda, Ariel, and Umbriel. Resonant configurations are set up by orbital evolution driven by tidal interactions, and the process of evolution into and out of resonance may involve periods of extremely large tidal dissipation, which may significantly affect the satellites' thermal histories and interior structures.

Tidal dissipation can be a long-lived heat source, completely independent of stellar radiation, and it might allow habitable planets or satellites to exist at a much wider range of distances from a much wider range of central stars than previously imagined. Europa, with its plentiful supply of water, may be one of these habitats, an environment that may be far more common in the universe than Earth-like planets orbiting Sun-like stars. Tidal dissipation was probably important to many large satellites, and to the Pluto/Charon system.

Interiors

For the majority of the satellites of the outer solar system, our knowledge of their interiors is limited to the mean density of the satellite (see Table 5.1), but the Galilean satellites, which have been visited by the Galileo spacecraft, are now much better understood. By measuring the tidal and rotational distortion of the satellites, the normalized moments of inertia about the rotation axes have been well constrained, leading to the following conclusions regarding the interiors of the Galilean satellites:[1-4]

- Io is differentiated into a large metallic core, roughly half the satellite's radius, surrounded by a silicate mantle.
- Europa has a 100 ± 25-km-thick H_2O layer, which is frozen at the surface and may be liquid beneath. The remainder of Europa's interior likely consists of a silicate mantle of density ~3,300 kg m^{-3}, surrounding a metallic core with a radius of 600 ± 150 km.
- Ganymede's metallic core was detected by the gravity measurements at the same time that its magnetic field was discovered. A model for Ganymede's interior consisting of an Io-sized core and mantle surrounded by 800 km of ice fits the gravity data and accounts for the metallic core required by the magnetic field.
- Callisto is not differentiated like Ganymede, despite the similarity in size and density. A significant metallic core can be ruled out, as can a completely undifferentiated structure. The intermediate value of Callisto's moment of inertia requires a layer of mixed ice and rock, which may extend all the way to the center. These conclusions are based on the reasonable assumption that Callisto is in hydrostatic equilibrium.

The very different fates of Callisto and Ganymede suggest that tidal heating is probably an important factor in satellite differentiation. Titan has undergone at least a partial differentiation resulting in a dense atmosphere of N_2 and other volatiles that are extremely rare or absent in the jovian satellites. Triton is currently degassing volatile species via geysers; moreover, Triton's surface displays evidence for vigorous cryovolcanic and tectonic processes, perhaps reflecting intense tidal heating and differentiation of its deep interior during capture into Neptune orbit.

The surface evolution of the smaller satellites offers intriguing clues about their interiors. Despite their relatively small sizes, Enceladus, Tethys, Ariel, and Titania all seem to have experienced some internally driven surface activity, indicating that internal evolution has occurred. Tiny Miranda has a complex tectonic history, which has likely been modulated by differentiation and/or tidal heating.

The thermal states of the interiors of the outer-planet satellites are coupled to their differentiation. Tidal heating is driving the continuing magmatic activity of Io and the ongoing loss of volatile elements (S, O, Na, K) from Io's surface, which affects the plasma environment throughout the jovian system. Ganymede's differentiated interior and actively convecting core (required to generate its magnetic field) may be a consequence of its passage into resonance, while Callisto has not experienced this history. The origin and persistence of liquid-water layers in icy satellites depend directly on their thermal histories. Galileo magnetometer observations of induced electrical currents in Europa, Ganymede, and Callisto imply that liquid-water layers exist in all three icy jovian satellites.[5,6] While the layers in Callisto and Ganymede are bounded by ice on both sides (high-pressure phases of ice are denser than liquid water, resulting in an ice-liquid-ice sandwich), Europa's liquid water—analogous to Earth's deep oceans—is most likely in direct contact with its silicate mantle. Tidal heating in Europa's ice is probably sufficient to stabilize its liquid layer for long periods, but other icy satellites may have only transient liquid layers.

Geological Processes

Cratering

Impact craters serve as probes of satellite crusts, indicators of surface age, and records of the impactor population through time.[7] Large impacts can penetrate completely through the brittle outer crust of an icy satellite to excavate deep (perhaps oceanic) material and may form a multiringed structure. Very large impacts may fracture a satellite's interior or potentially disrupt a large satellite. Relaxation of crater topography (or the absence of relaxation) can be indicative of the past thermal gradient. High-resolution imaging of the Galilean satellites suggests that the number of small impactors in the outer solar system may be much less than estimates extrapolated from the lunar flux.[8] One implication is that impact gardening and regolith generation are less effective on outer-planet satellites than on the terrestrial planets.

Sun-orbiting (heliocentric) impactors are expected to produce markedly more craters on the leading hemisphere of a synchronously rotating satellite than on its trailing hemisphere. For the saturnian satellites and Triton, crater size-frequency data show complexities attributable in part to planet-orbiting (planetocentric) impactor populations.[9,10] Recent flux estimates and dynamical simulations that include the newly recognized effects of Kuiper Belt and Oort cloud cometary impactors indicate higher fluxes and therefore younger satellite surface ages than previously estimated. For example, by these estimates, Triton's plains are on average only ~100 million years old, and Europa's surface is just ~50 million years old.[11,12] The mounting evidence indicates that some large outer-planet satellites have been active worlds for much of solar system history.

Tectonics

The large satellites display a broad array of tectonic features interpreted as the manifestation of extensional, compressional, and strike-slip deformation.[13,14] Extensional structures are especially prevalent on many of the midsized icy satellites of Uranus and Saturn and on Triton, potentially the manifestation of global expansion during freezing of interior water or differential cooling of their surfaces and interiors. Lanes of subparallel ridges and troughs on Miranda, Enceladus, and Ganymede may share analogous origins as regions of concentrated extension and icy volcanism, analogous to some terrestrial rift zones. Individual ridges on saturnian satellites and sets of ridges on Enceladus may be due to compression, perhaps from global cooling and contraction or from convection.

Galileo imaging of the large jovian satellites has revolutionized our understanding of large-satellite tectonics. Io has mountains that soar to 17 km tall, probably formed as volcanic materials piled onto the surface, placing the entire lithosphere into compression.[15,16] Callisto shows enormous multiringed structures, which at high resolution consist of normal fault scarps and graben.[17] These and similar concentric structures on Ganymede and Europa probably formed when large impacts penetrated through the satellites' brittle lithospheres to mobile material below—plausibly liquid water. Ganymede displays an array of extensional tectonic structures, notably lanes of bright "grooved terrain," likely formed by normal faulting of a cold, ice-rich lithosphere above warmer, more ductile ice.[18] Grooved terrain may be linked to satellite differentiation, during which high-density ice polymorphs were displaced from the deep interior resulting in volume expansion of the whole moon.

The varied tectonic styles of Europa hint at a sub-ice ocean (Figure 5.2).[19] The satellite's bright plains are crisscrossed by narrow troughs and enigmatic double ridges, with a morphological sequence from simple struc-

FIGURE 5.2 Europa displays a wide variety of surface forms, including these so-called ridged plains. These features consist of many parallel, crosscutting ridges, often arranged in pairs. Dark material appears to be located primarily in the valleys between the ridges, suggesting that the dark material may be moving down the flanks of the ridges and collecting along their bases. This image shows a region some 20 km across and reveals features as small as 26 m. North is at the top, and the Sun illuminates the surface from the upper left. Courtesy of NASA/JPL.

tures to wider and more complex ones. The origin of these ridges is uncertain, but suggestions include diapiric intrusion, shear heating, diking, water-rich extrusion, and compression along preexisting tectonic structures. Wider pull-apart bands may represent complete separation of the icy lithosphere, in a manner broadly analogous to terrestrial seafloor spreading.

The global pattern of lineaments matches stress predictions if gravitational torques from Jupiter have induced nonsynchronous rotation of Europa's icy shell, implying decoupling of the surface from the interior, likely by a liquid-water ocean. Systematically varying stress directions and magnitudes induced by diurnal orbital flexing of Europa's icy shell can elegantly explain Europa's cycloidal-shaped ridge and fracture patterns and may drive strike-slip faulting along ridges and bands.[20,21] Significant tidal amplitude is necessary to produce large diurnal stresses, and this argues strongly for a subsurface liquid layer[22,23] but does not constrain its depth.[24] Large-scale folds have been recognized on Europa, but these can compensate for only a small fraction of Europa's ubiquitous extension.[25]

Volcanism and Geysers

The discoveries of current eruptive activity on Io and Triton were highlights of the Voyager 1 and 2 missions.[26,27] In the inner solar system, geologic activity is driven primarily by early accretion and differentiation and the slow decay of radioactive nuclides, with the result that continuing geologic activity was only expected on planets such as Earth and Venus with sufficient silicate mass. By analogy, no current geologic activity was expected on outer-planet satellites. This paradigm was altered by Voyager and by our new understanding of the effects of orbital evolution, tidal heating, and highly volatile crustal species.

Io has several hundred currently active, high-temperature silicate eruptions (Figure 5.3)[28] and a global average heat flow ~20 times greater than that of Earth.[29] Many of these lavas have extremely high temperatures and may be rich in Mg, similar to Archean komatiites and lunar mare basalts.[30] Voluminous flood volcanism, which has had pronounced effects on Earth's climate, is ongoing at Io. The high heat flow, Mg-rich and flood volcanism, and rapid tectonism, which we can directly observe on Io, provide insights into ancient processes on the terrestrial planets. In addition, the giant (up to 500 km) volcanic plumes of Io and the smaller geyserlike eruptions on Triton provide fundamental experiments in fluid dynamics.

Many other icy satellites exhibit evidence for past icy volcanism, expressed as smooth plains, ridges, lobate deposits, and mantling deposits.[31] Active volcanism on some icy satellites is plausible today, based on the lightly cratered surfaces of Europa and Enceladus and models of atmospheric processes on Titan. Although Galileo yielded no evidence for active volcanism on Europa,[32] continued searches are warranted.

Diapirism

Interior material also can be brought to the surface of a satellite though diapirism, in which buoyancy forces due to a density inversion cause mobile material to pierce and rise through a higher-density overburden.[33] On the icy satellites, Triton's pitted "cantaloupe" terrain offers the most dramatic example of a surface apparently turned inside out by diapirism, perhaps owing to compositional layering of various frozen volatiles. Triton's record of intense diapirism may reflect capture by Neptune and consequent tidal heating. Diapirism may also explain the unusual rounded "coronae" of Miranda—a satellite potentially frozen during the act of differentiation—perhaps induced by tidal heating.

Europa also may exhibit evidence of diapirism.[34] Pits, domes, and spots on Europa have been interpreted as the surface manifestations of thermally induced diapirism, where warm ice, probably in contact with a subsurface ocean, has risen through colder and denser ice above. Larger "chaos" regions on Europa consist of disrupted crustal blocks situated in a hummocky matrix (Figure 5.4). These also have been inferred to be the manifestation of diapirism and associated partial melting of the ice crust, though complete melting of a thin ice shell is an alternative hypothesis. Diapirs may be able to transport nutrients and/or organisms between the surface and subsurface ocean of Europa and other icy satellites.

Atmospheres, Surface Chemistry, and Interactions

The thin atmospheres and volcanism of Io and Triton serve to redistribute and modify volatile deposits on their surfaces. However, the Cassini-Huygens mission may reveal much more dramatic effects on Titan from an active "hydrologic" cycle associated with liquid hydrocarbons. The surface of Titan may be modified by methane and ethane rainfall and liquid hydrocarbon erosion, active ground-fluid processes, and littoral processes (Figure 5.5).

Titan

As does Earth, Titan has an atmosphere that is primarily nitrogen and a surface pressure of 1.5 bars. Titan's thermal profile indicates that methane (~10 percent abundance) and many minor organic constituents should exist in both liquid and gas phase and should rain out of the atmosphere, providing a liquid component to the surface.[35,36] Titan's liquid cycle, with clouds, rain, and perhaps seas, may resemble our terrestrial counterpart, with several key

FIGURE 5.3 The margin of the lava flow field associated with the Prometheus volcanic plume on Jupiters' moon Io. This entire area is under Prometheus's active plume, which is constantly raining bright material onto the surface. The darkest regions, having margins similar to those formed by fluid lava flows on Earth, are believed to be relatively young because they are not yet covered with plume fallout and are, perhaps, too warm for bright gas rich in sulfur dioxide to condense. The older, brighter plains to the upper right are covered by ridges formed, possibly, by the folding of the surface or by deposition or erosion. The bright streaks emanating from the lava flow margins may arise where hot lava vaporizes sulfur dioxide. This image has a resolution of 12 m and was taken by the Galileo spacecraft on February 22, 2000. Courtesy of NASA/JPL.

FIGURE 5.4 This image from the Galileo spacecraft is a very high resolution view of the Conamara Chaos region of Jupiter's moon Europa. It shows an area where icy plates have been broken apart and moved around laterally in a hummocky matrix. Corrugated plateaus end in icy cliffs more than 100 m high; debris piled at the base of the cliffs can be resolved down to blocks the size of a house. The fracture running horizontally just above the bottom of the image is about the width of a freeway. Courtesy of NASA/JPL.

differences. Titan's main condensable is methane rather than water. Titan's atmosphere is more massive and cooler than that of Earth. Titan receives ~100 times less solar insolation, the energy that fuels terrestrial weather. In contrast, Titan has roughly 100 times more latent heat available for fueling weather than does Earth. Recent observations indicate the sparse presence of daily clouds that uniformly lie at the tropopause.[37] In addition, ground-based observations, recorded in the past two decades, show evidence for the unique occurrence of a hurricane-sized cloud system.[38] The formation mechanisms of clouds, the origin of the large and rare storm, and the effect of latent heat on cloud evolution and circulation are unknown, because only limited measurements of the lower atmosphere have been possible. Current and future investigations aim to understand Titan's coupled atmosphere and surface, which may provide analogs for processes important on Earth.

Improved understanding of Titan's evolution depends on knowledge of the depths and extent of its liquid reservoirs at and near the surface. The main atmospheric constituent, nitrogen, dissolves in methane. Therefore, the size and composition of the reservoirs reflect not only the total inventory of organics but also the amount of

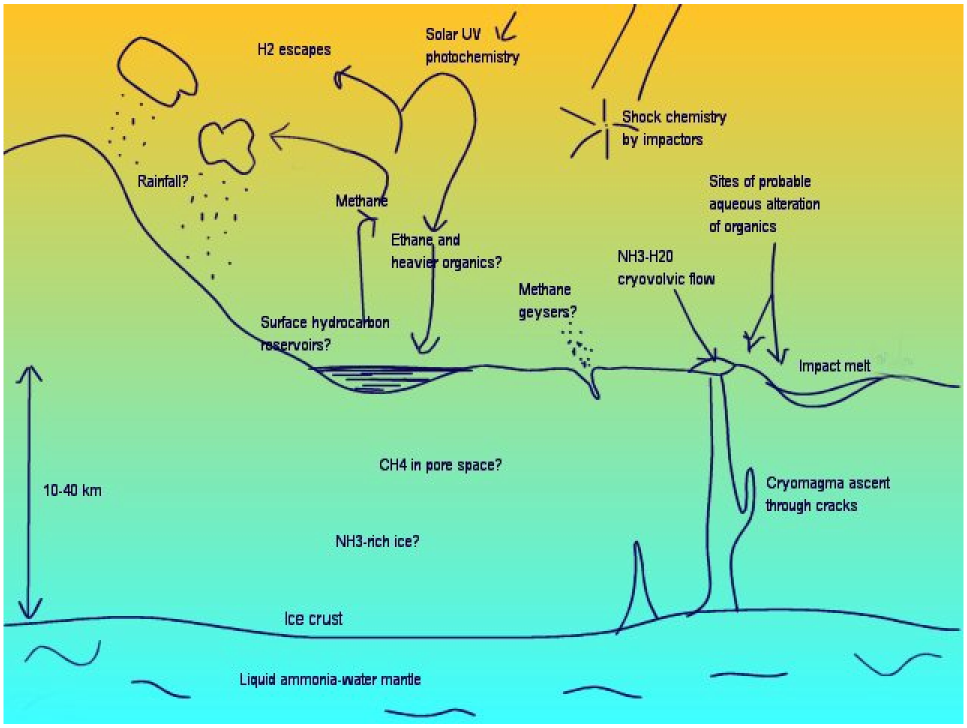

FIGURE 5.5 A schematic of the dominant processes affecting the volatile inventory on Titan and the formation of prebiotic molecules. Courtesy of Ralph Lorentz, University of Arizona.

nitrogen on Titan. The rapid and irreversible destruction of methane by solar ultraviolet photolysis indicates the need for a recent supply. Two extreme scenarios are possible: Current geologic activity may directly supply atmospheric methane (and lead to an atmosphere that varies in size with supply), or large near-surface reservoirs of methane, such as seas, may exist.[39,40]

Organic chemistry on Titan occurs both in the stratosphere and on the surface. In Titan's stratosphere, the photolysis of methane coupled with electron dissociation of nitrogen instigates a rich organic chemistry, for which over a dozen organic species have been identified. The end-product of this chemistry, Titan's ubiquitous haze, consists of complex organic material with an elemental composition that has not yet been directly measured. Even the ratio of nitrogen to carbon in Titan's haze is unclear. Laboratory simulations of this satellite's photochemistry produce solid residues having optical properties similar to those of Titan's haze. Their elemental composition hints that alkanes, aromatic compounds, heteropolymers, and amino acids, key initial compounds in life's chemistry, are constituents of Titan's haze.[41]

Chemical reactions at Titan's surface proceed very slowly, potentially in cold (94 K) organic liquids. In this environment, organic chemistry evolves in a solvent over a long time period, well shielded from ultraviolet radiation, as on Earth. Yet Titan's atmosphere and surface are more reduced than Earth's (similar to Urey-Miller models of early Earth), conditions are cool, and the solvent is mainly hydrocarbon (methane and ethane). It is possible that the solids are not soluble in the surface liquids. At present, however, the composition of Titan's surface organics is poorly known and is inferred primarily from our understanding of the atmosphere. The path and extent of long-term organic evolution in a largely nonaqueous solvent are unknown. Titan provides us with a laboratory for this chemistry.

Titan has, on brief occasions, experienced chemical conditions more like those on Earth. Episodic heating, due to impacts and possibly volcanism, probably exposed organic material on Titan's surface to aqueous solutions. Liquid-water ponds ~0.5 km deep would survive on Titan's surface for as long as 1,000 years. Considerations of reaction rates relevant to these brief events indicate the ready production of compounds (such as purines, pyrimidines, aldehydes) important to prebiotic chemistry.[42] At present, our understanding of organic chemistry is too poor to estimate how quickly life arose on Earth. Titan provides us with snapshots of this chemistry at 100- to 10,000-year intervals, longer than possible in laboratories and shorter than can be deciphered from our terrestrial record. Titan's natural laboratory may uniquely hold answers to the evolution of prebiotic chemistry on ancient Earth.

Triton

Four separate ices have been identified spectroscopically on Triton's surface: N_2, CH_4, CO, and CO_2.[43,44] The latter three species (except perhaps CO_2) exist partially in solid solution with N_2, the main constituent. More complex organic molecules are also expected to be present as a result of photolysis and radiolysis. Triton's surface temperature of approximately 38 K creates an atmosphere in vapor pressure equilibrium with the ices, which is highly responsive to heating changes associated with solar insolation and the variable photometric and compositional properties of the surface. As a result, the atmosphere experiences large-scale sublimation, transport, and recondensation of N_2, CO, and CH_4. Another unique characteristic is Triton's geyserlike plumes that entrain dark dust and rise 8 km above the surface.[45] A diffuse haze pervades the atmosphere; it probably consists of the condensation of hydrocarbons created by photochemistry. Discrete clouds, likely condensed N_2, are present near the poles.

Io

Io's sulfur-rich chemistry reflects the moon's active volcanism.[46] Io's infrared spectrum is dominated by the signature of solid SO_2. The albedo, continuum spectrum, and atmospheric measurements indicate, however, that other sulfurous materials are present. The surface topography and hot-spot temperatures require the presence of silicates, which are largely covered by the sulfur-rich veneer.

Io's atmosphere is arguably the least understood in the solar system. It is uniquely affected by ubiquitous and time-variable volcanism, which adds to the atmospheric inventory through plumes and affects the surface temperature and composition. Ground-based spectroscopy identified the primary constituent, SO_2, and two of the minor components, SO and S_2.[47,48] The surface pressure is around 1 nanobar and varies spatially by orders of magnitude. The vertical profile is poorly characterized. Two limiting, although related, origins are postulated: an atmosphere produced by sublimation of SO_2, and one produced by volcanic outgassing. The atmospheric structure is unclear and may be determined by several processes: hydrostatic equilibrium, plume dynamics, and general circulation driven by large pressure gradients. The roles of these processes are not well known and require knowledge of the surface properties (porosity, composition, and temperature), the atmospheric temperature and composition, atmospheric escape processes, and the composition and energetics of the plumes.

Icy Satellites

In addition to water ice, which by the 1970s had been identified on most of the icy satellites by ground-based spectroscopy, the surfaces of these bodies contain non-ice material, which may be composed of mixtures of silicates and carbonaceous material as well as components produced by charged-particle bombardment of their surfaces. Galileo's spectral measurements have also identified features due to CO_2, C-H, S-H, and C≡N on several of the Galilean satellites.[49] Similar materials have been identified in spectra of interstellar ice grains. This non-ice component presumably represents a mixture of material originally accreted with the satellites, subsequent comet and asteroid impacts, and components implanted and/or modified by magnetospheric environments. On Europa, the presence of heavily hydrated sulfates has been inferred, including sulfuric acid and sulfate salts. Charged-particle irradiation of ice-rich surfaces can break molecular bonds, allowing recombination to form new compounds, as discussed below.

Iapetus is of special interest because the dark material on the leading hemisphere (albedo of 3 percent) is inferred to have an organic component. Its spectrum is consistent with a mixture of laboratory-synthesized organics (termed tholins), poly-HCN, and the Murchison organic residue.[50] The nature and origin of the dark material is unclear. The strong asymmetry with respect to the direction of orbital motion suggests some external control if not external origin.

Magnetospheric Processes and Interactions

Sputtering/Implantation

The large satellites of the gaseous giant planets spend all or most of their time in the corotating magnetospheres of these planets. The interaction of satellite and corotating plasma modifies the satellites' surfaces and atmospheres and leads to a net loss of volatile materials to the magnetospheres. At the present time, Io is known to lose more than a ton per second of volatile material (mostly S and O) to Jupiter's magnetosphere.[51] Similarly, Europa is losing its icy surface at the rate of ~2 cm per million years (Myr) to Jupiter's magnetosphere.[52] Ganymede's magnetic field partially shields the equatorial regions from plasma bombardment. However, it is estimated that the polar regions of Ganymede lose an average of 8 mm/Myr of ice from sputtering.[53] Callisto, in a more benign radiation environment, loses <0.4 mm/Myr of ice to sputtering. The plasma bombardment of icy surfaces results in the implantation of S derived from Io's torus into the crusts of icy satellites.[54] The irradiation of icy satellite surfaces also results in the production of H_2, O_2, H_2O_2, and other stable oxides that get embedded in the ices and also form tenuous atmospheres near the surface.[55] The irradiation of other ice contaminants such as C and S produces CO_2, SO_2, and H_2SO_4. The radiolysis of the surface by magnetospheric particles continuously cycles S between SO_2, H_2SO_4, and polymer S forms.[56] At Europa, the fast recycling of the crust (believed to occur over a time scale of 100,000 to 10 million years) may deliver oxidants from the surface to the subsurface ocean.[57] These oxidants could fuel life in the absence of sunlight.

Style of Plasma Interaction

The type and strength of satellite/magnetospheric interaction depends on the satellite's size, surface composition, and electrical conductivity, the presence or absence of an internal magnetic field in the satellite, and the density, composition, and speed of the interacting plasma. Based on these factors, three distinct types of interactions have been observed. In the nonconducting type of satellite/plasma interaction, as in the case of Callisto, the magnetospheric plasma slams into the satellite and is absorbed, but sputters some volatile material off the satellite's surface.

A second type of interaction, called the conducting-satellite/plasma interaction, is best illustrated by Io and Europa. Because of a well-developed ionosphere at Io and large plasma pickup near Europa, most of the magnetospheric plasma is diverted around the moons. Only a small fraction of the incoming plasma flux strikes the moons and sputters volatile materials off the surface. The strong Alfvén wing currents generated in the interaction are closed in the ionosphere of Jupiter where they generate visible footprints (see Figures 4.3 and 4.4).

The third type of interaction is epitomized by Ganymede, which generates its own internal magnetic field.[58] Ganymede's magnetic field is strong enough that it creates a minimagnetosphere of its own in Jupiter's magnetosphere, partially shielding the satellite from plasma bombardment. The interaction between Ganymede's magnetosphere and Jupiter's magnetosphere is similar to the interaction between Earth's magnetosphere and the solar wind, in which magnetic reconnection plays a key role.

Curiously, the other three Galilean satellites were found not to have internal fields at present. However, it is likely that some or all of the other large moons of the solar system were endowed with an internal magnetic field at some time in their evolution.

Induced Fields

Europa, Ganymede, and Callisto. Magnetic observations from the vicinities of Europa, Ganymede, and Callisto show that all three moons generate electromagnetic induction fields in response to the rotating field of Jupiter.[59,60] The magnetic signatures are consistent with the presence of subsurface electrically conducting shells in these bodies. Detailed analyses for Europa and Callisto suggest that liquid subsurface oceans with thicknesses exceeding a few kilometers could account for the enhanced subsurface conductivities.[61] Geological and geophysical lines of evidence are consistent with liquid subsurface oceans within Europa and Ganymede. However, the presence of electromagnetic induction from geologically inactive Callisto was indeed a surprise.

Titan. The only spacecraft to make in situ observation of the interaction of Titan with Saturn's magnetosphere was Voyager 1, which flew through the plasma wake of Titan. No appreciable internal magnetic field was observed (surface field strength <30 nT).[62] The main pickup ion is N^+, and the integrated surface pickup rate is ~10^{24} ions per second. The geometry of the flyby was not suitable to infer the presence or absence of an electromagnetic induction signature, so magnetic measurements cannot yet speak to the question of an ocean within Titan.

SPACE MISSIONS FOR LARGE SATELLITE EXPLORATION

Spacecraft exploration represents the cutting edge of research in addressing the key scientific questions (see the section "Unifying Themes and Key Scientific Questions for Large Satellite Exploration," below) that are related to the theme of this chapter—"Active Worlds and Extreme Environments." The missions considered here range from currently launched and flying (Cassini) missions to those with extensive design already completed (Europa Geophysical Explorer, with significant heritage from Europa Orbiter), to future mission concepts with varying degrees of design and study (e.g., Titan Explorer, Europa Landers, Neptune Orbiter). Input on the characteristics and potential capabilities of these missions came from a variety of sources—project briefings, studies by NASA Centers, industry, NASA advisory committee studies and reports, and studies by National Research Council panels (particularly COMPLEX). In evaluating the potential of these missions for addressing key scientific questions, the Large Satellites Panel had to reach a common understanding regarding mission and experiment capabilities. Naturally, varying degrees of uncertainty occur in this process as one moves from well-understood missions and payloads to future candidates for which multiple mission options and possible payloads are still being vigorously discussed. The following is a brief description of the key elements that the panel considers to be related to each mission, largely on the basis of studies by the Jet Propulsion Laboratory. While details will change as these (and future) mission concepts evolve, the panel believes them to be representative of the types of missions and measurement capabilities available for the period under study.

Missions were considered within three broad cost categories: large, medium, and small. At present, experience indicates that the dollar cutoffs between these categories are about $750 million and $500 million, although cost estimates will change as the missions become better defined and as new technologies become practical. The nature of the large satellites considered in this panel's study and the missions required for major advances over current knowledge (developed primarily from flyby reconnaissance) dictate that many of the high-priority missions would be at least in the medium and most probably in the large category. The costs of high-energy launch vehicles, radioisotope power systems, long flight times, and radiation-hard electronics all contribute to this situation. Of particular concern is the fact that several of the panel's candidate missions are poorly studied to date. These missions are very challenging by the standards of inner planet missions and even past outer planetary reconnaissance. The panel urges more complete and competitive studies of these mission candidates for understanding their true costs and capabilities.

Large Missions

Cassini-Huygens

The Cassini mission with the Huygens Titan probe was launched in 1997. It will go into orbit around Saturn in July 2004 and will deploy the Huygens probe into Titan's atmosphere in January 2005. For its evaluation of Saturn satellite scientific issues, the panel assumed a successful primary Cassini mission and appropriate mission data analysis. A principal target of the mission is Titan. Huygens results, combined with Cassini's orbital remote sensing and in situ sampling of the upper atmosphere, should revolutionize our understanding of this satellite's atmosphere, its structure and composition, and the complex chemical processes occurring in it. Huygens descent data and mapping by several of Cassini's instruments (radar, imaging, and near-infrared spectroscopy) should provide a first close look at its haze-shrouded surface, identify landforms and possible regions of liquid hydrocarbon lakes or seas, and give an indication of the age and history of its surface. High-precision gravitational measurements will place constraints on its internal structure and history, and may be able to determine if there exists a subsurface liquid-water-rich layer in this satellite. Studies of the other satellites in the system will also be important, providing information on the history and evolution of the satellite system, the interactions of the satellites with Saturn's magnetospheric environment, and the origin of the dark, presumably organic-rich material on the enigmatic satellite Iapetus.

Europa Geophysical Explorer

The Europa Geophysical Explorer mission is designed to follow up and significantly expand upon the remarkable discoveries made by the Galileo mission, suggesting that Europa may have a global liquid-water ocean beneath an ice crust that may be only a few kilometers to tens of kilometers thick. The primary objectives of the mission, as defined by the Europa Orbiter Science Definition Team, can be split into two groups in terms of their priority. The highest-priority, or Group 1, objectives are as follows:

- Determine the presence or absence of an ocean;
- Characterize the three-dimensional distribution of any subsurface liquid water and its overlying ice layer;
- Understand the formation of surface features, including sites of recent or current activity; and
- Identify candidate landing sites for future lander missions.

The lower-priority, or Group 2, objectives are the following:

- Characterize the surface composition, especially compounds of interest to prebiotic chemistry;
- Map the distribution of important constituents on the surface; and
- Characterize the radiation environment in order to reduce the uncertainty for future missions, especially landers.

Complementary discussions of Europa objectives are contained in COMPLEX's 1999 report, *A Science Strategy for the Exploration of Europa*.[63] For the present study, the panel has assumed the basic capabilities and "strawman" payload described in the 1999 Europa Orbiter Announcement of Opportunity:[64] at least a 30-day mission in orbit, detailed gravity and altimetry measurements of the tides (with ~1-m accuracy), ice-penetrating radar, and an integrated camera/remote-sensing package. The panel also assumes (and recommends) some augmentation to this payload, including a magnetometer and some surface compositional experiment(s) capable of meeting the Group 2 objectives. In addition, the panel assumes that some significant data will be returned during the Jupiter orbital tour phase of the mission from multiple Europa, Ganymede, and Callisto flybys and from more distant observations of Io.

Europa Pathfinder Lander

The panel considered two levels of potential landed science at Europa. The Europa Pathfinder concept involves a small (~10- to 20-kg) payload delivered to the surface from an orbiting spacecraft using a retro-propulsion system and airbags to achieve landing. Total system mass is in the vicinity of ~200 kg, including the retro-propulsion and airbag landing systems. A key feature of the mission studied to date is a compact lander body capable of operating from an arbitrary landed attitude.

Proposed instrumentation could include a sophisticated geophysical station with seismic/acoustic sensors, a magnetometer, and possibly a tilt meter, combined with surface elemental and phase composition measurements of the immediate vicinity of the lander using some combination of optical, infrared, Raman spectrometer, and Laser Induced Breakdown Spectroscopy (LIBS) techniques. No subsurface sampling, sample handling, or preparation systems are envisioned for the Europa Pathfinder. In addition to data relayed from the lander to the orbiter, complementary orbital science is assumed, with the details to be determined by results of the Europa Geophysical Explorer mission. Technology needs include airbag and landing systems for the Europa environment.

Europa Astrobiology Lander

A more ambitious Europa mission concept involves a study of organic chemistry and possible biosignatures from a landed station. The science rationale and some of the experiment concepts for such a mission have developed recently in a series of workshops sponsored by the Europa Focus Group of the NASA Astrobiology Institute, and are complementary to objectives developed by the 1999 NASA Campaign Science Working Group for Prebiotic Chemistry in the Outer Solar System, but no complete system/mission studies of the concept have been performed.

The key elements that distinguish this candidate mission (which could also carry some of the same payload as that on the Europa Pathfinder Lander) are the inclusion of subsurface sampling capability to obtain material that is less processed by radiation (at depths greater than approximately 10 cm) and sample handling and sample preparation for a sophisticated chemical analysis suite, including a gas chromatograph/mass spectrometer and the coring instrument. This greatly extends the compositional capability, and particularly the characterization of organic materials, from that envisioned for the Europa Pathfinder, but with a significant increase in complexity and cost (unquantified at present).

As does the Pathfinder, this concept assumes either prior Europa Geophysical Explorer data for global context and/or orbital science on its own supporting orbiter delivery spacecraft. In addition to radiation-hard electronics, this class of mission requires significant technology development in the experimental areas of highly compact and sophisticated chemical analysis systems.

Titan Explorer

It is expected that Cassini-Huygens results will set the agenda for the future exploration of Titan. However, a number of studies of mission concepts that would form the basis for future exploration of Titan's atmosphere and surface have already been discussed. These are based on anticipation of what Cassini-Huygens will accomplish and also on its known limitations. On the basis of these studies, the panel assumed a generic Titan Explorer that would be capable of addressing many key questions in the relevant areas. The mission assumes the use of aerocapture at Titan to deliver an orbiter and an atmospheric "aerobot."

The key elements of the proposed exploration are mobility within the atmosphere so that different levels, weather, and processes can be studied in detail with in situ experimentation, including aerosol collectors, mass spectrometers, and other atmospheric structure and composition instrumentation. In addition, the system is assumed to be capable of making high-resolution remote observations of the surface from various altitudes and of descending to the surface multiple times during the mission to make close-range and possibly in situ measurements of surface composition and properties. Although landed packages delivered by the atmospheric vehicle have also been discussed in various combinations with the atmospheric experimentation, the panel assumes the simpler (single aerobot with surface landing capability) for its evaluation at this time. The orbiter is assumed to have limited communications and some science capability, perhaps focused on global context for the Titan Explorer data and studies of the stratospheric regions not reached by the aerobot.

Technology-development needs include a range of technologies for the aerobot (or other forms of atmospheric mobility), as well as advanced radioisotope power sources for long-life operations.

Uranus Orbiter

An orbiter mission to Uranus is assumed to be able to address key satellite objectives through repeated flybys of the five major satellites in the system. Geological, geophysical, and geochemical characterization of the satellites should be equivalent to that achieved for the Galilean satellites by Galileo and anticipated for the Saturn system from Cassini-Huygens. A suite of remote-sensing camera/spectrometer systems and space physics instrumentation for studying magnetosphere-satellite interactions is assumed.

Neptune Orbiter

The Neptune Orbiter mission was of particular interest to this panel because of the opportunity to study Triton, a world known to have intriguing volcanic and atmospheric activity despite its low surface temperatures. For its purposes, the panel assumes that such a mission would include repeated flybys of Triton with an instrument suite equivalent to that of the Galileo or Cassini orbiter systems. As noted below, this mission is only feasible using advanced technology for solar electric propulsion combined with advanced aerocapture or nuclear-electric propulsion to achieve orbit with an acceptable payload/flight-time combination.

Medium Missions

Io Observer

The mission concept for Io involves either a Jupiter orbiter dedicated to multiple close flybys of Io or a multirole mission, with part of the mission and payload being devoted to magnetospheric space physics goals and/or atmospheric and auroral observations. The assumption that this mission could achieve the stated goals within this cost category rests partially on assuming that heritage from the Europa Geophysical Explorer would allow significantly reduced costs. A suite of remote-sensing experiments is assumed, with emphasis on the monitoring of Io's active volcanism and related processes.

Ganymede Orbiter

The Ganymede Orbiter mission is similar in concept to the Europa Geophysical Explorer, but the impracticable goal of measuring Ganymede's very small tides is replaced by an increased emphasis on Ganymede's internally generated magnetic field and its interaction with that of Jupiter. No detailed studies are yet available, and the assumption that this mission could achieve the stated goals within this cost category rests partially on assuming that the lesser radiation environment and heritage from the Europa Geophysical Explorer mission would allow significantly reduced costs.

Neptune Flyby

The Neptune Flyby mission concept would be similar to the Kuiper Belt-Pluto Explorer discussed in Chapter 1, but with a considerably expanded payload to achieve multiple objectives for Neptune, the ring system, the magnetosphere, and Triton. The panel assumes that modern instrumentation designed for the study of Triton based on current knowledge from the Voyager flyby in 1989 could make a major advance over our current knowledge of Triton. The major limitation for observations of such an active world is that it obviously would provide only a brief snapshot of the Neptune system, and cannot definitely determine the presence or absence of a subsurface water layer via variations in the induced magnetic signature.

Small Missions

For the reasons discussed earlier, dedicated missions to achieve major results in large satellite science rarely fit realistically in the small category. Other types of science investments requiring resources in the range of those required by Discovery-class missions or below can, however, make major contributions to large satellite science, although they are not, strictly speaking, new missions. Examples include the following:

- *Extended/enhanced missions, for example, a Cassini extension.* Once the investment in a major mission is made, it is frequently possible to derive very high science benefit from extending the lifetime and/or objectives where other resources permit. Past examples include the Voyager Uranus and Neptune missions, Galileo's extended exploration of Europa and Io, and the addition of asteroid encounters to Galileo's mission and a Jupiter encounter for Cassini. A near-term opportunity is the likely extension of the Cassini orbital mission beyond the nominal 4-year prime mission. Detailed planning for an extended mission has not yet been undertaken, but several possible scenarios could result in major new Titan and/or icy satellite results for costs equivalent to, or less than, those for a single low-cost mission.
- *Ground- and space-based telescopes.* The use of telescopic observations of all sorts has been of tremendous importance to solar system science and to satellite studies in particular. Investments in the continuing use and upgrading of current facilities and instrumentation, as well as the development of new systems, are vital parts of a balanced strategic program. (See the more detailed discussion in the following subsection.)

Key Enabling Technologies for Large Satellite Exploration

New technologies create opportunities for enhancing and/or enabling missions by a combination of increasing capabilities, decreasing resource use (mass, power, volume, and so on), and lower cost. Many of the key technologies are related to all or most of the missions considered in this section. These include the following:

- *Telemetry.* Maintenance of essential Deep Space Network capabilities is crucial to all future missions. In the period of time considered by this survey, significant improvements in systemwide telemetry capability are expected to be needed in order to handle the data requirements from increasingly sophisticated instrumentation and the large number of potential deep-space missions. This is particularly true for missions related to large satellite objectives, owing to their location in the outer solar system and to the time-criticality of some mission phases.
- *Power systems.* All past and current missions targeting the large satellites of the outer solar system have relied on radioisotope power systems because of the large heliocentric distances, long flight times, and requirements for reliability and radiation tolerance involved. Maintenance of this capability is critical for most if not all of the outer solar system missions considered in this study. Additional improvements in efficiency and design of these systems are highly desirable for the more ambitious missions involving landed packages and surface or atmospheric mobility.
- *Radiation-hard electronics, shielding, reliability and fault tolerance.* All outer solar system missions involve, to some degree, long lifetimes, high reliability, and tolerance to reasonably large total radiation exposure from solar, galactic, and planetary magnetospheric sources. Many of the highest-priority large satellites (e.g., Europa and Io) reside in extremely high radiation environments. Improvements in radiation-hard components and design are essential to future exploration of these worlds.
- *Microelectronics/autonomy.* More capability in smaller packages is a key component in achieving difficult science goals within mass, dollar, and power constraints. Hardware and software advances in this area, coupled with the radiation tolerance and reliability requirements noted above, are critical for making future missions capable of reaching their science goals.

• *Propulsion.* Outer-planet missions in general, and particularly missions to satellites residing deep in the gravity wells of large planets, are severely limited by the physics of propulsion—the rocket equation—which dictates very small payload mass fractions compared with propulsion mass for current chemical systems. Technology development in the area of electric propulsion is one important component in improving this situation in the future.[65] Unfortunately, current solar-electric and future nuclear-electric technologies do not offer large benefits for the mission types considered here, except for Neptune Orbiter. Nuclear-electric systems could potentially yield huge improvements in payload mass and capability for more distant, future missions with large energy requirements.

• *Aerocapture.* The use of a planet's or satellite's atmosphere to slow an approaching spacecraft is another approach to solving the low-payload-mass problems noted above. The precursor technology of aerobraking has already been demonstrated at Venus and Mars. Further research into materials, structures, and techniques required for full aerocapture are necessary in order for future missions to take advantage of this technique. Titan orbiters and atmospheric explorers are one highly promising use of this technology. One of the potential missions of great interest for both large satellite and giant planet research—the Neptune Orbiter—requires either solar-electric propulsion combined with advanced aerocapture capability or nuclear-electric propulsion to achieve an acceptable payload and mission capability.

• *Planetary protection.* Many of the satellites in this study are potentially interesting for the study of organic chemistry, prebiotic chemistry, and environments of biological interest. Examples include organic-rich Titan and satellites that may have liquid subsurface oceans. Exploring these environments while maintaining an acceptably low risk of contaminating them with terrestrial organisms poses new challenges. Improvements and research in techniques of planetary protection are needed to address these issues for future missions.

Supporting Research for Large Satellite Exploration

Many previous NRC and NASA advisory reports have stressed the importance of both adequate resources for mission data analysis and a strong, ongoing research and analysis program in solar system science. It is particularly important to emphasize these areas in a strategic study such as this, because their relationship to what is usually seen as the major science activity of NASA—that is, flying missions—is complex and frequently misunderstood. Research related to solar system exploration in the current era is unusual in that it is funded almost entirely by only one office within one federal agency (NASA). Other disciplines in physics, astronomy, and the geosciences typically are supported by programs in multiple agencies and offices, university programs, industrial research, and even state-sponsored research programs.

The idealized, academic view of NASA's relationship to the solar system research community is that NASA flies the missions that the researchers say are most important and then supplies the data to the community, which proceeds to go about the business of "doing science" with it. In reality, mission and research activities are so closely coupled within NASA that the very research designed to utilize data from past missions and develop the scientific basis and instrumentation for future missions is often in direct competition for scarce resources with the missions themselves. These areas must be given equal weighting with individual missions to arrive at a strong program of solar system exploration.

The panel considers four closely connected types of research:

- Mission data analysis,
- Research and analysis,
- Laboratory studies, and
- Earth-based astronomy.

Mission Data Analysis

Each mission has a core group of researchers involved directly with the mission and its experiments. In addition, there is always a wider group of scientists with particular interests in the mission's objectives who independently participate in the analysis of mission data at various levels. Typically, mission data-analysis programs fund the acquisition and initial analysis of mission data during the mission's active phase and for some years afterward, frequently with a broadened pool of research proposals. The split between what are regarded as direct project costs and costs that are part of the broader R&A budget has varied from mission to mission over time.

Research and Analysis

As noted above, R&A is not always cleanly separable from data analysis, but generally is the program area that funds researchers to perform what is frequently referred to as "basic research" in the field. This includes theoretical, observational, and experimental studies and the analysis of data from many sources, not just one mission.

Laboratory Studies

Laboratory studies are, of course, one aspect of R&A, but historically they have been viewed separately, because support commonly requires substantial investment in acquiring and maintaining relatively large-scale and costly equipment.

Earth-Based Astronomy

Ground- and space-based telescopic studies have been important to the development of our understanding of large satellites dating back to the discovery of Jupiter's moons by Galileo Galilei and Simon Marius in 1610 and continuing to the present day with observations of Io's volcanoes, Titan's surface, and spectroscopy of many satellites. These observations and many more provide the basis for formulating the planetary exploration missions, instrumentation, and experiments that have led to our current state of knowledge. Telescopic observations also play a vital role in supporting and extending the results from missions, commonly changing our way of analyzing these results or prompting further investigations, often while the mission is still active. Capabilities from the ground and from Earth orbit strongly complement those of missions by uniquely enabling the following:

- Long-term studies of, for example, the seasonal response of Titan's and Triton's atmospheres and the rapid evolution of Io's surface;
- Investigations of rare events, such as major volcanic eruptions on Io and large cloud systems, or "storms," on Titan;
- Measurements with instruments that are not yet feasible for spacecraft observations, and the development of new techniques and instrumentation for future space applications;
- Continual studies of satellites before and after space missions that frame questions and provide temporal context; and
- Technical support for the success of spacecraft missions, such as the ongoing determination of wind fields on Titan, needed to track the Huygens probe.

At present, planetary astronomy is supported primarily through NASA's Infrared Telescope Facility, a 3-m telescope on Mauna Kea, for which half the time is allotted to planetary investigations. In addition, limited observing opportunities exist on the Hubble Space Telescope and large ground-based systems (such as the Keck telescopes). The IRTF plays a key role in planetary research, with state-of-the-art infrared instruments, quick response to time-critical events, and a scheduling facility that allows the investigation of long-term planetary phenomena. Continued maintenance and upgrading of these facilities are essential for future planetary satellite research.

Mission development and scientific return and fundamental research also require state-of-the-art capabilities from the ground, such as the proposed Giant Segmented Mirror Telescope (GSMT), and the James Webb Space Telescope (JWST) in Earth orbit. The advantage of a GSMT, with an accompanying advance in adaptive optics, is the increased spatial resolution and sensitivity to faint sources. A GSMT can address questions such as the weather on Titan, the vertical structure of Io's atmosphere and its temporal evolution, volcanic activity and surface changes on Io, and the seasonal wind field on Titan. To address these and other topics, planetary astronomy must play an active role in the scientific strategies for the proposed large-aperture systems.

UNIFYING THEMES AND KEY SCIENTIFIC QUESTIONS FOR LARGE SATELLITE EXPLORATION

The Large Satellites Panel evaluated and organized key scientific questions around four major themes that, in its opinion, best capture the most important scientific questions pertinent to large satellites. They are as follows:

- *Origin and evolution of satellite systems.* Tidal heating and orbital evolution have led to complex histories for some large satellites. Satellite systems may form and evolve in ways analogous to planetary systems but are much more accessible for detailed study than are extrasolar planetary systems.
- *Origin and evolution of water-rich environments in icy satellites.* Evidence for water within the icy Galilean satellites has led to a new paradigm for the potential habitability of planetary systems. Europa offers the greatest potential for finding life, because the subsurface water may interact with the surface and the silicate mantle.
- *Exploring organic-rich environments.* Although organic materials are common in the solar system, only Earth and Titan allow the study of organic chemistry in the presence of a thick atmosphere, a solvent, and a solid surface. Titan may enable study of the conditions leading to the origin of life.
- *Understanding dynamic planetary processes.* We can best understand physical processes by observing them in action, and satellites such as Io, Titan, and Triton offer a broad range of current activity, from the interiors to the surfaces, atmospheres, and magnetospheres.

Origin and Evolution of Satellite Systems

The satellite systems around the giant planets were formed by processes reasonably analogous to those that formed the solar system. The proximity of these satellite systems (as opposed to extrasolar planetary systems) allows detailed study of the results of four different accretional "experiments." The extrasolar planetary systems observed to date tend to contain giant planets, and the apparent rarity of terrestrial planets within a few astronomical units of the central star makes understanding the origin and evolution of satellite systems a step toward understanding the origin and evolution of extrasolar planetary systems. Study of the jovian system has revealed the importance of resonant orbital interactions in the evolution of satellite systems. Io demonstrates the importance of tidal heating in providing an energy source for internal dynamics, while Europa may provide an example of a habitat that depends on this energy, an idea that has considerably broadened our concept of habitable worlds. Exploration of the outer-planet satellites contributes to our understanding of how the orbital and thermal evolution (coupled through tidal interactions) of satellites and satellite systems leads to the development of habitable environments. The following key questions emerge as the most important next steps toward understanding the origin and evolution of satellite systems:

- How do conditions in the protoplanetary nebula influence the compositions, orbits, and sizes of the resulting satellites?
- How do factors such as size, composition, orbital evolution, and tidal heating influence the differentiation and outgassing processes in large and midsized satellites? In particular, why is Titan the only large satellite with a thick atmosphere?
- To what extent are the surfaces of icy satellites coupled to their interiors (chemically and physically)?
- How has the impactor population in the outer solar system evolved through time, and how is it different from the inner solar system?
- What does the magnetic field of Ganymede tell us about its thermal evolution, and do other large satellites have intrinsic magnetic fields?

Origin and Evolution of Water-Rich Environments in Icy Satellites

Perhaps the most significant question that humankind can ask and effectively address about the universe around us is, Are we alone? In the coming decade and continuing into the decade beyond, solar system exploration has the opportunity to make significant advances toward answering the question of whether life does or can exist beyond Earth in the solar system. Based on Galileo results, a new paradigm has emerged in which many, if not most, large icy satellites that circle cold gas giant planets in the solar system and other planetary systems contain liquid-water oceans. This paradigm shift implies that the habitability zone around our star and other stars is extended to include circumplanetary belts surrounding Jupiter-sized planets. Four top-level questions emerge:

- Can and does life exist in the internal ocean of an icy satellite?
- What combination of size, energy sources, composition, and history produce long-lived internal oceans?
- What is the distribution of internal water, in space and time?
- What is the chemical composition of the water-rich phase, and does surface chemistry reflect interior ocean composition?

Exploring Organic-Rich Environments

Titan's wealth of organic material and its possible seas uniquely resemble those of Earth. Titan illuminates the organic chemistry that proceeds in more reduced environments than Earth's. It is an intact chemical laboratory where ultraviolet photolysis and electron bombardment initiate the synthesis of carbon and nitrogen that ultimately forms complex organic solids in the stratosphere. Less well understood is the long evolution of chemistry at Titan's surface, where both organic liquid and solid precipitates are predicted. In addition, Titan is believed to support a liquid cycle involving atmospheric methane vapor and surface liquids. As such, clouds form over bodies of liquid, rain occurs, and the circulation responds to the release of latent heat, as on Earth. Yet, on Titan the energetics driving these events differs from the terrestrial experience. Titan provides us with a new perspective on weather processes inherent to our home planet. Most important, it serves as a natural laboratory in which complex prebiotic chemistry may have evolved. The following top-level questions emerge:

- What are the chemistry, distribution, and cycling of organic materials on Titan?
- Is Titan internally active, producing water-rich environments with potential habitability?
- What are the current state and the history of Titan's surface?
- What drives the meteorology of Titan?
- Has there been climate change on Titan?
- Could Titan support life forms that do not require liquid water?

Understanding Dynamic Planetary Processes

The outer-planet satellites are natural laboratories for a diverse range of physical and chemical processes of great interest to scientists and those who value science. These processes cannot be studied in small artificial laboratories, and some of them, such as active flood volcanism, cannot be studied in nature on our own planet. Io is the most extreme example of an active world that includes vigorous mantle convection, volcanism, tectonism, atmospheric loss, and magnetospheric interactions. Cracking, faulting, and diapirism in Europa's ice shell are probably still active. Ganymede has an active core and magnetosphere. Titan has active meteorology, atmospheric chemistry, and perhaps active "fluvial" and volcanic processes. Enceladus must somehow have supplied the E ring of Saturn. Triton has active geysers and perhaps active glaciers and diapirism. Magnetospheric sputtering and implantation modify many satellite surfaces. Perhaps the best way to illustrate the rich science potential is to list the relevant key questions in three categories:

- *What are the active interior processes and their relations to tidal heating, heat flow, and global patterns of volcanism and tectonism?* Specifically: What is the nature and history of Ganymede's active core? Does Io have a magma ocean? Are there active magmatic processes in Europa's silicate core? Do Titan, Triton, Enceladus, or other satellites have active interiors?

• *What are the currently active endogenic geologic processes (volcanism, tectonism, and diapirism) and what can we learn about such processes in general from these active worlds?* Specifically: What can Io's high heat flow, ultramafic lavas, large-scale eruptions, and tectonics tell us about ancient geologic processes on the terrestrial planets? How active is the fracturing, faulting, and diapirism in Europa's ice shell, and how often does liquid water reach the surface? Are there active volcanic or tectonic processes on Titan? What drives the geysers on Triton: solar or internal energy?

• *What are the complex processes and interactions on the surfaces and in volcanic or geyserlike plumes, atmospheres, exospheres, and magnetospheres?* Specifically: How can the dynamics of plumes on Io and Triton be explained? Do any other satellites have active venting? What can be learned about planetary meteorology from Titan? How active is Titan's "hydrologic" cycle, and how does it modify the surface? Can Io-like magnetospheric interactions enable discovery of large satellites around extrasolar jovian planets? How do satellites lose volatiles and atmospheres?

Key Measurement Objectives for Exploring Large Satellites

Table 5.2 summarizes this panel's effort to quantify measurement objectives and rate the capabilities of current and future missions in meeting those objectives. For each key scientific question, the panel identifies several critical measurement objectives. Because a measurement objective may be met by using several different techniques, the suite of instruments that should be included in the payload of each of the missions is not explicitly identified. If a measurement objective is not applicable or is unachievable by a mission, this is designated by "—". However, if a significant advance in understanding of that measurement objective would occur from a mission, the mission is assigned a single "x." Major advances are signified by "xx," and any expected breakthroughs in understanding are indicated by "xxx."

Through this approach, missions to Europa and Titan stand out as the highest priority. This analysis also illustrates that a flyby-type mission such as the Neptune Flyby fairs poorly in the rating matrix because many important measurement objectives can only be met from the global and/or temporal coverage provided by an orbiting spacecraft or from in situ surface measurements from a lander. It should be noted that the Uranus Orbiter also fares poorly compared with the Neptune Orbiter, because dynamic Triton is especially interesting. These results are incorporated into Table 5.3 in the section below, together with a discussion of mission targets.

RECOMMENDATIONS OF THE LARGE SATELLITES PANEL TO THE STEERING GROUP

Rationale for Recommendations

As detailed above (see Table 5.2), there are several key questions answers to which would lead to major scientific advances or breakthroughs in characterizing the outer solar system's large satellites. However, spacecraft missions and other initiatives with costs approaching a billion dollars must do more than advance scientific disciplines. They must address the most basic questions of importance to all of humanity, such as the questions that motivate this survey: Are we alone? Where did we come from? What is our destiny? The Large Satellites Panel has identified four relevant, high-priority questions that can be addressed through the continued study of large satellites. They are as follows:

1. Is there extant life in the outer solar system?
2. How far toward life does organic chemistry proceed in extreme environments?
3. How common are liquid-water layers within icy satellites?
4. How does tidal heating affect the evolution of worlds?

TABLE 5.2 Key Scientific Questions, Measurement Objectives, and Mission Capabilities for Large Satellites in the Outer Solar System

Scientific Themes/ Key Questions	Measurement Objectives	Cassini-Huygens	Titan Explorer	Europa Geophysical Explorer	Europa Pathfinder Lander	Europa Astrobiology Lander	Io Observer	Ganymede Orbiter	Neptune Flyby	Neptune Orbiter	Uranus Orbiter	Earth-Based Telescopes	Laboratory
A. Origin and Evolution of Satellite Systems													
1. How do conditions in the protoplanetary nebula influence the compositions, orbits, and sizes of the resulting satellites?	Interior structure and composition of (major) satellites	x	xx	xx	xx	xxx	x	x	x	x	x	—	x
	Secular variation of orbital parameters	—	x	x	xx	xx	x	x	—	x	x	xx	—
	Extrasolar planetary system observations	—	—	—	—	—	—	—	—	—	—	xxx	—
	Characterization of magnetic fields in satellites	x	xx	xx	xx	xx	xx	xxx	x	xx	x	—	—
2. What affects differentiation, outgassing, and the formation of a thick atmosphere? (Why is Titan unique?)	Atmospheric composition	xxx	xxx	—	—	—	xx	x	xx	xxx	—	x	x
	Production/loss rates	xx	xxx	xx	xx	xx	xx	xx	x	xx	x	x	x
	Interior structure and composition	x	xx	xx	xxx	xxx	x	x	x	x	x	—	x
	Characterization of internal heat sources	xx	xx	xxx	xx	xxx	xxx	x	x	x	x	—	—
3. To what extent are the surfaces of icy satellites coupled to their interiors (chemically and physically)?	Geologic processes/history (including impacts)	xxx	xxx	xx	xx	xx	xx	xx	x	xx	xx	x	x
	Tectonics/volcanism	xx	xxx	xx	xxx	xxx	xxx	xx	x	xxx	xx	x	x
	Map surface composition	xx	xx	xx	x	x	xx	xx	x	xxx	xx	xx	x
	Transport processes	x	xxx	xx	xx	xxx	xx	x	x	x	x	x	x
	Subsurface sounding	x	x	xx	xxx	xxx	x	xx	—	xx	xx	—	—
4. How has the impactor population in the outer solar system evolved through time, and how is it different from the inner solar system?	Observation of craters (on many different bodies)	xx	x	xx	x	x	x	x	x	xx	xx	x	—
	Sky surveys/KBOs	—	—	—	—	—	—	—	—	—	—	xxx	—
	Geology/modification	xx	xx	xx	—	—	x	x	—	xx	xx	—	x
	Absolute age determination	—	xxx	—	xxx	xxx	—	—	—	—	—	—	—
5. What does the magnetic field of Ganymede tell us about its thermal evolution, and is Ganymede unique?	Internal magnetic fields	x	x	x	x	x	xx	xxx	—	x	xx	—	—
	Plasma/ionospheric observation of external field	xx	x	xx	x	x	xxx	x	xx	xxx	xxx	x	—
	Transport processes	x	xx	xx	xx	xx	xx	x	x	x	x	x	x

B. Origin and Evolution of Water-Rich Environments in Icy Satellites													
1. What is the chemical composition of the water-rich phase?	Remote and in situ composition observations	xx	xxx	xxx	xx	xxx	x	xx	x	xx	xx	x	x
2. What is the distribution of internal water, in space and in time?	Geology/stratigraphy	xx	xx	xx	xx	xx	—	xx	x	xx	xx	—	x
	Subsurface sounding	x	x	xxx	xxx	xxx	—	xx	—	xx	x	—	x
	Internal structure	xx	xx	xx	xxx	xxx	—	xx	—	xx	xx	—	—
	Elemental and isotopic composition	xx	xx	—	xx	xxx	x	x	—	x	x	x	—
3. What combination of size, energy sources, composition, and history produce long-lived internal oceans?	Heat flow	—	—	—	—	xx	xx	—	—	x	—	—	—
	Geology	xx	x	x	x	x	—	x	x	x	x	—	—
	Secular variation of orbital parameters	—	—	—	—	xx	—	—	—	—	—	xx	—
	Composition	x	xx	xx	xx	xxx	—	xx	x	xx	xx	x	x
	Internal structure	x	xx	xx	xxx	xxx	—	xx	x	xx	x	—	—
	Intrinsic magnetic field (past/present)	xx	xx	xx	xx	xx	—	xxx	—	xx	xx	—	—
4. Can and does life exist in the internal ocean of an icy satellite?	Search for evidence of biology and organic compounds at surface and in the deeper interior	x	xxx	xx	xx	xxx	—	x	x	x	x	x	x
	Sample water layers	—	—	—	—	—	—	—	—	—	—	—	—
	Characterization of surface radiation environment	x	xx	xx	xx	xx	x	xx	x	xx	x	—	—
	Characterization of chemistry of surface and ocean	x	xx	xx	xx	xxx	—	xx	x	xx	x	x	—
	Life in extreme environments (Earth analogues)	—	—	—	—	—	—	—	—	—	—	—	xxx
	Transport processes	x	xx	xxx	xx	xx	x	xx	x	xx	xx	—	—
C. Exploring Organic-Rich Environments													
1. What is the nature of organics on large satellites?	Composition (elemental, isotopic, and molecular), remote and in situ	xxx	xxx	x	xx	xxx	x	xx	xx	xxx	xx	xxx	—
	Production/loss (radiation, degassing, escape, lightning, and exogenic/endogenic)	xxx	xxx	x	xx	xxx	x	x	xx	xxx	x	x	x
	Physical state	xxx	xxx	x	xx	xx	x	x	xx	xx	x	x	xx
	Optical properties	xx	xx	x	x	x	x	x	x	x	x	x	xxx
	Reaction rates/kinetic information	xxx	xx	x	x	x	x	x	x	x	x	—	xxx
2. What are the processes currently affecting organic-rich surfaces?	Fluvial processes	xxx	xxx	—	—	x	—	—	—	—	—	—	—
	Impact processes	xxx	xx	xx	—	x	—	x	x	xx	x	x	x
	Cryovolcanic processes	xxx	xxx	xx	xx	xx	x	—	xx	xxx	x	x	x
	Tectonic processes	xx	xx	x	xx	xx	x	x	x	xx	x	—	—
	Aeolian processes	xx	xx	—	—	—	—	—	x	xxx	—	—	—
	Chemical (and radiation) processes	xx	xxx	x	xx	xx	—	x	x	x	x	xx	xx

continues

TABLE 5.2 Continued

Scientific Themes/ Key Questions	Measurement Objectives	Cassini-Huygens	Titan Explorer	Europa Geophysical Explorer	Europa Pathfinder Lander	Europa Astrobiology Lander	Io Observer	Ganymede Orbiter	Neptune Flyby	Neptune Orbiter	Uranus Orbiter	Earth-Based Telescopes	Laboratory
C. Exploring Organic-Rich Environments *(continued)*													
3. How does organic chemistry evolve in a hydrocarbon solvent?	Composition (elemental, isotopic, and molecular) of liquid phase	x	xxx	—	—	—	—	—	—	—	—	—	—
	Transport processes	xx	xxx	—	—	—	—	—	—	—	—	—	—
	Reaction rates/kinetic information	x	x	—	—	—	—	—	—	—	—	—	xx
	Disequilibrium (life?)	x	xxx	—	—	—	—	—	—	—	—	—	xx
4. How do atmospheric processes affect organic chemistry?	Production/loss (radiation, degassing, escape, lightning, and exogenic/endogenic)	xx	xxx	—	—	—	—	—	x	xx	—	x	—
	Tropospheric meteorology	xx	xxx	—	—	—	—	—	—	—	—	xx	—
	Stratospheric meteorology	xxx	x	—	—	—	—	—	—	xx	—	xx	—
	Physical and chemical properties of the condensables	xxx	xx	—	—	—	—	—	x	xx	—	—	—
	Composition (elemental, isotopic, and molecular), remote and in situ	xx	xx	—	—	—	—	—	x	xx	—	xx	xx
	Reaction rates/kinetic information	—	—	—	—	—	—	—	—	—	—	—	xx
D. Understanding Dynamic Planetary Processes													
1. What are the active interior processes and their relations to tidal heating, heat flow, and global patterns of volcanism and tectonism?	Interior structure	x	xx	xx	xxx	xxx	x	xx	x	xx	x	x	x
	Heat flow and tidal heating	xx	xx	x	xx	xxx	xxx	xx	x	xx	x	xx	x
	Global volcanism and tectonism	x	xx	xx	x	x	xxx	xx	xx	xxx	x	x	x
	Secular variations of magnetic field	xx	xx	xxx	x	x	xxx	xxx	—	xxx	x	x	x

2. What are the currently active endogenic geologic processes (volcanism, tectonism, diapirism) and what can we learn about such processes in general from these active worlds?	Observations of dynamic processes with high spatial and temporal resolution	x	xx	xx	xx	xx	xxx	x	x	xxx	x	—	—
	Composition of recent surface deposits, plumes or geysers, and atmospheres	x	xxx	x	xx	xx	xx	x	x	xx	x	xx	x
	Seismic or acoustic observations	—	—	—	xxx	xxx	—	—	—	—	—	—	x
	Search and discovery of new types of activity	xx	xxx	xxx	xx	xx	xxx	x	xx	xxx	x	x	—
3. What are the complex processes and interactions on the surfaces and in volcanic or geyserlike plumes, atmospheres, exospheres, and magnetospheres?	Dynamics of plumes, geysers, atmospheres, exospheres, and magnetospheres	xx	xxx	xx	x	x	xxx	x	xx	xxx	x	xx	x
	History of volatiles	x	xxx	xx	xx	xxx	xxx	x	xx	xxx	x	xx	x
	Atmospheric loss (fields and particles)	xx	xx	xx	x	x	xxx	xxx	x	xxx	x	—	—

NOTE: xxx = breakthrough, xx = major advance, x = significant advance in understanding, — = not applicable.

The first question directly addresses the major exploration theme "Are we alone?," and the second question directly addresses the theme "Where did we come from?" The third and fourth questions address habitability, in this and other planetary systems, which is relevant to all three overriding themes, including "What is our destiny?"

Mission Targets

What is the best strategy to address these questions? Europa and Titan stand out as the highest-priority targets. Each is the key to one of the high-priority questions listed above, and each addresses one major exploration theme and is important for others (Table 5.3).

Europa is the satellite that holds the most promise for understanding the potential habitability of icy satellites. Convincing evidence exists for the presence of water within just a few to tens of kilometers from the surface, and there is evidence for the recent or ongoing transfer of material between the surface and the water layer. Europa's ocean is probably in direct contact with a rocky mantle below and so potentially with hydrothermal systems, and surface and intra-ice oxidants transported to the ocean may be able to nourish oceanic organisms. The first step in understanding the potential for icy satellites as abodes for life in the universe is to send a spacecraft to Europa, in order to confirm the presence of an interior ocean, to characterize the satellite's ice shell, and to understand its geological history. Europa is also key to addressing high-priority questions 3 and 4, above. It is the best target for theme B—origin and evolution of water-rich environments in icy satellites—and is important to themes A (see Table 5.3) and possibly themes C and D . Given the high cost of the Europa Geophysical Explorer, the panel

TABLE 5.3 Targets and Missions for Future Exploration

	Best Targets	Missions
Theme		
A. Origin and evolution of satellite systems	Satellite systems	Cassini-Huygens, Europa Geophysical Explorer, Neptune Orbiter, Uranus Orbiter
B. Origin and evolution of water-rich environments in icy satellites	Europa	Europa Geophysical Explorer, Europa Pathfinder Lander, Europa Astrobiology Lander
C. Exploring organic-rich environments	Titan	Cassini-Huygens, Titan Explorer
D. Understanding dynamic planetary processes	Io, Titan, Triton	Cassini-Huygens, Io Observer, Titan Explorer, Neptune Orbiter
High-Priority Questions		
1. Is there extant life in the outer solar system?	Europa	Europa Astrobiology Lander
2. How far toward life does organic chemistry proceed in extreme environments?	Titan	Titan Explorer
3. How common are liquid-water layers within icy satellites?	Triton, Titan, Enceladus, Callisto, Ganymede, Europa	Cassini-Huygens, Europa Geophysical Explorer, Neptune Orbiter, Ganymede Orbiter
4. How does tidal heating affect the evolution of worlds?	Io, Europa, Ganymede, Triton, Enceladus, Miranda	Io Observer, Europa Geophysical Explorer, Neptune Orbiter, Ganymede Orbiter, Cassini-Huygens, Uranus Orbiter

considers it essential that the mission address both the Group 1 and Group 2 science objectives described by the Europa Orbiter Science Definition Team and that it contribute to Jupiter system science (theme A) during the ~2-year Galileo-like tour prior to capture into Europa's orbit.

Titan is a unique natural laboratory for organic chemistry, unlike any other environment in the solar system, and clearly the prime target for theme C—exploring organic-rich environments—and high-priority question 2, How far toward life does organic chemistry proceed in extreme environments? Titan's atmosphere not only creates this scientifically interesting environment, but also facilitates future exploration via aerocapture and airborne mobility. Titan may also have a subsurface water layer and could prove to be a promising location to search for past or extant life or its precursor chemistry, and it is important to several other themes and questions (see Table 5.3).

It cannot now be predicted whether Europa or Titan will ultimately prove to be the most promising satellite for long-term exploration. However, Cassini-Huygens will surely revolutionize our understanding of Titan, so it is premature to plan a subsequent Titan mission in detail. Another consideration is that any mission to the outer solar system requires a decade or more from the initial design to the end of the mission. Therefore, a logical approach is to continue to alternate between Europa and Titan missions that overlap in time. Cassini-Huygens followed Galileo, so the next mission should be to Europa, then a new mission to Titan. Any mission to Europa or Titan that significantly advances our objectives is likely to be expensive. International collaboration is important scientifically and may prove essential to adequately fund these endeavors.

The other large satellites are also providing significant exploration opportunities. Whole satellite systems must be studied in order to address theme A—the origin and evolution of satellite systems. Theme D—understanding dynamic planetary processes—leads us principally to Io and Triton in addition to Titan, as well as Ganymede, Europa, and Enceladus. High-priority questions 3 and 4 lead us to all of the six largest satellites and to Enceladus and Miranda.

Ground-Based Supporting Facilities

The panel recommends continued support for the IRTF along with the proposed adaptive optics upgrade in order to enhance the scientific results of the Cassini-Huygens exploration of Titan. While the IRTF will continue to provide necessary support for planetary astronomy, it is a relatively small telescope, and many future investigations require larger apertures, on the order of a ~20- to 30-meter-class telescope. The advantage of such a telescope, for example, GSMT, with an accompanying advance in adaptive optics techniques, is the increased spatial resolution and sensitivity to dim sources. A GSMT would provide about 18,000 resolution elements across the disk of Io at opposition, allowing the study of the energetics of Io's volcanoes by resolving many compositionally and energetically distinct regions on the satellite's surface (Figure 5.6). It would resolve large Titan storms, providing information on Titan's weather. The GSMT would clarify the vertical structure of Io's atmosphere through occultations. It would better characterize the spectra of dark, likely organic, solids on satellite surfaces. In addition, the GSMT would enable critical mission support: for example, if it were available, it could better determine Titan's wind field and thus lead to better tracking of the Huygens probe.

Summary of Panel Recommendations

Based on the summarized findings presented in Tables 5.2 and 5.3, the SSE Survey's Large Satellites Panel ranks its recommendations as follows.

Small Initiatives

1. Cassini-Huygens, with preparation for enhanced science analysis and an extended mission
2. Continued support for Earth-based telescopes, to include the acquisition of an appropriate amount of GSMT observing time

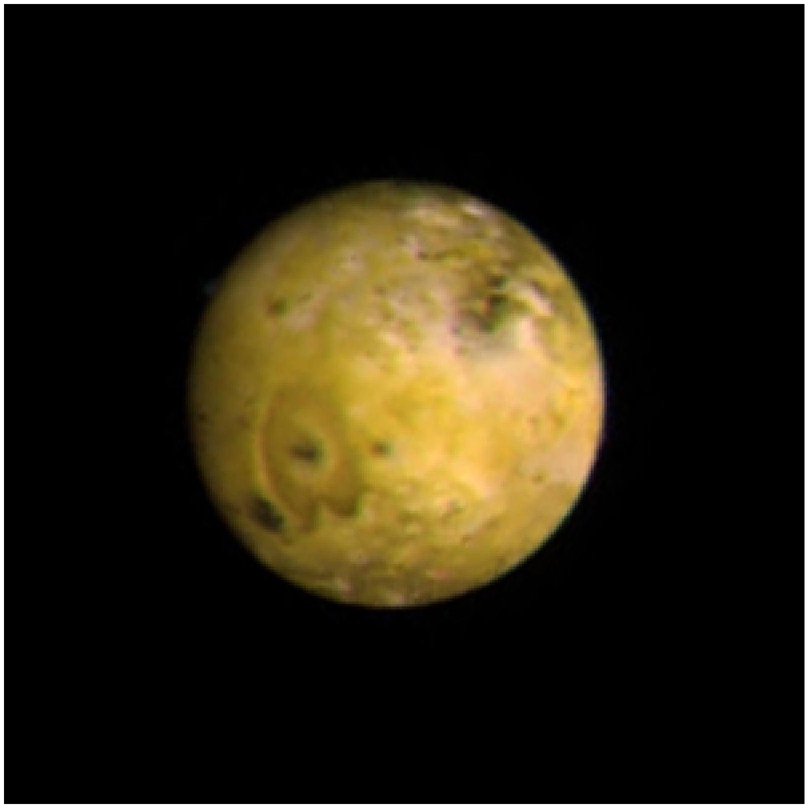

FIGURE 5.6 This Voyager 1 image of Io, the innermost of Jupiter's Galilean satellites, has a spatial resolution approximately the same as that from a 30-meter-aperture, Earth-based telescope equipped with active optics. Such a telescope would provide researchers with the ability to monitor the eruptions of Io's numerous volcanoes on a regular basis for a period of years to decades. The pear-shaped plume of the volcano Pele is just visible on Io's upper-left-hand limb in the original image. Courtesy of NASA/JPL.

Medium Initiatives

1. New technology developments to support future missions
2. Io Explorer
3. Ganymede Orbiter

Large Initiatives

1. Europa Geophysical Explorer
2. Titan Explorer
3. Europa Lander (Pathfinder or Astrobiology)
4. Neptune Orbiter

New Technology

Technology initiatives that are needed are ranked below and follow from the recommendations outlined above:

1. Radiation-hard electronics—for Europa Geophysical Explorer and future Europa landers and Io Observer,
2. Advanced telemetry and power systems—for all deep-space missions,
3. Atmospheric mobility—for Titan Explorer,
4. Compact organic chemistry laboratory—for Titan Explorer and Europa landers,
5. Planetary protection—for Europa landers,
6. In situ age-dating—for Europa landers and Titan Explorer, and
7. Solar-electric propulsion and aerocapture or nuclear-electric propulsion—for Neptune Orbiter.

Although the technology recommendations above follow logically from the panel's science and mission rankings, technologies may be developed for other reasons. For example, the administration's FY 2003 budget proposal includes funding for nuclear-electric propulsion. Once nuclear-electric propulsion is developed, this capability would then open up new mission possibilities, such as a spacecraft that could sequentially orbit all three icy Galilean satellites. Why not postpone the Europa Geophysical Explorer mission until nuclear-electric propulsion is available? There are several good reasons for not postponing this important mission. First, nuclear-electric propulsion is not expected to be ready for an actual mission for at least 10 years, and this panel considers Europa exploration too scientifically important to postpone it for a decade. Second, an orbiter around Europa is far more important for the panel's key objectives than are orbiters around Callisto or Ganymede, because Europa's tides are much larger (i.e., measurable via altimetry) and because its ice shell is significantly thinner (permitting radar sounding). Study of Callisto and Ganymede is important to understand this class of icy satellite, but multiple flybys of these two moons expected from the Europa Geophysical Explorer will provide key information on the surface morphology and composition, upper crustal structure, and magnetospheric interactions. The subsequent step in Europa exploration should be a landed mission, which also requires a Europa orbiting spacecraft, and nuclear-electric propulsion and other new technologies may then enable a more capable mission.

Finally, the panel emphasizes that strong support for adequate R&A is essential to all future initiatives.

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Part Two

An Integrated Strategy for Solar System Exploration

The material in Part One, together with community input received in various forms, provides the basis for the strategy for solar system exploration outlined in Part Two of this report. This broad strategy addresses all aspects of the Solar System Exploration program: its motivations, its infrastructure, future and present missions, its relationship to other programs in NASA and elsewhere in government, and supporting ground-based facilities.

Chapter 6 addresses the motivations for the program, briefly describes the strengths and weaknesses of important elements of the program's infrastructure, and makes recommendations for addressing the latter. It makes clear why solar system exploration is a compelling activity today.

Chapter 7 presents the results of the Solar System Exploration Survey's analysis of the many scientific questions raised in Part One and identifies 12 key scientific questions that the SSE Survey believes are most appropriate to address in the period 2003-2013. Relating these questions to candidate missions suggested to the Survey the scientific basis for the system of flight mission priorities and supporting ground-based priorities presented in Chapter 8.

6

Solar System Exploration Today: A Multifaceted Endeavor

Solar system exploration is a grand human enterprise that seeks to discover the nature and origins of the celestial bodies among which we live and to explore whether life exists beyond Earth.

MOTIVATIONS: WHY SOLAR SYSTEM EXPLORATION COMPELS US TODAY

To appreciate our place in the universe, we must understand the neighborhood in which we reside. We want to know how planets formed, what determined their characteristics, and why at least one of them became an abode of life. How haphazard was this formation? Do Earth-like planets typically survive, or are they usually swallowed by Jupiter-like objects, pushed into their parent stars, or flung into the vastness of interstellar space? Is life a rare phenomenon, or is it the expected outcome of solar system formation? The answers to these profound questions may be contained in the orbits, masses, compositions, gaseous and plasma environments, and surface and internal structures of solar system objects. We may understand yet more by scrutinizing the planets orbiting other stars.

The solar system evolves. Planetary and satellite surfaces record ancient histories of violent impacts, volcanic eruptions, crustal tectonics, and fluid erosion. Planetary rings continually change, active geology is at work on the solid bodies in the outer solar system, and Titan's atmosphere supports ongoing organic synthesis. Mars's climate and internal dynamics have changed dramatically over time. Earth-crossing asteroids and comets threaten us. Will we and our planetary home survive? Some day people may live on other planets. By investigating these environments, we can better prepare for our future and perhaps predict the destiny of our species.

Could life have developed on other solar system objects? Recent discoveries suggest that the "habitable zone"[a] is not defined simply by distance from a star. Liquid water appears to be seeping out of the frozen cliffs of Mars and likely lies beneath the icy crust of Europa. Life on Earth survives extreme environments. Organic molecules and chemical-energy sources are ubiquitous beyond our planet, and the ingredients of familiar terrestrial life—water, carbon, and nitrogen—may have been brought to Earth's surface by asteroids and icy comets. Life itself may have been strewn across the solar system's archipelago by the impacts of comets and asteroids.

[a]Throughout this report, the word "habitable" is used in a general sense meaning compatible with any kind of life. When used to mean compatible with human life, the text is qualified as such.

Exploration of the solar system can reveal how likely we are to find life elsewhere in the universe and how it might be recognized. Just as studies of extreme but rarely visited terrestrial environments have revealed novel microbial species and unanticipated microbial ecosystems, so the detailed exploration of the solar system also might revolutionize our ideas about the diversity of life and the range of conditions in which it might originate and/or survive.

The scrutiny of the solar system provides other examples against which to compare Earth. It also helps us comprehend better how our world operates and how it evolves. The study of the solar system as a whole, and of the individual bodies within it, helps us understand how the entire family of planets formed and how planetary systems might develop around other stars. It therefore leads us to wonder whether other Earth-like planets can sustain life.

When we discuss life in the context of solar system exploration, it must be clearly understood that success or failure is not measured according to whether or not we actually find life beyond planet Earth. It is just as important to know that life does not exist in a particular locale, because this may lead to the development of an understanding of the environmental conditions necessary for life's existence. This suggests that life-related studies must be intimately connected to studies of the origin and evolution of planetary environments. Therefore, to assess the habitability of, for example, Mars requires a thorough understanding of that planet's tectonic, magmatic, hydrologic, and climatic evolution, including geochemical cycles of biological relevance, the development of potential habitats, and the processes responsible for the preservation and destruction of biomarkers.

To truly appreciate the apparent uniqueness of Earth, we must understand its rocky siblings: Mercury, Venus, and Mars, as well as the Moon. To uncover clues to the origin and evolution of the solar system and other planetary systems, we must learn about the giant planets and their satellites and ring systems. To understand our beginnings, we must examine samples from the solar system's oldest and most primitive bodies: comets and asteroids.

These issues concerning our place in the cosmos derive from three of the most profound questions that can be posed about the human condition: Are we alone? Where do we come from? What is our destiny? These deceptively simple questions have motivated a broad range of human endeavors, including exploration of scientific subjects as diverse as cosmology and biology. Nowhere are they more applicable than in solar system exploration.

Planetary exploration is also driven in part by our species' seemingly insatiable desire for knowledge and the application of that knowledge to improve the human condition. Such aspirations may be realizable as insight into natural processes and phenomena that affect human society, potential mitigation of hazards to Earth that arrive from space, and provision of knowledge about space resources that are available for utilization. The unquenchable human desire to explore, again ostensibly to improve the human condition, encourages many citizens. And who knows what role is played by the yearning of humans to know ourselves and to comprehend our place in the universe? In the words of T.S. Eliot:

> We shall not cease from exploration
> And the end of all our exploring
> Will be to arrive where we started
> And know the place for the first time.
>
> —T.S. Eliott, "Little Gidding," *Four Quartets*

A major motivation for much solar system research is to understand, at a fundamental level, the manner in which planetary bodies function. Various scientific disciplines—geology, meteorology, and space plasma physics, for instance—once pertained solely to Earth. Today they are enriched by being addressed in the broader context of the whole solar system rather than with a lone example. This comparative approach can be oversold, but some substantial advances in understanding are indeed being realized by investigating planetary processes as they apply in different settings: high-temperature volcanism on Io, differences in the climates of terrestrial planets, and substorms in Mercury's magnetosphere, for example.

Since time immemorial, a driving impulse for science has been to understand the threats that the natural environment poses to civilization. Some hazards, such as disease, fire, flood, and earthquake, are obvious and have long been the subjects of intensive scientific research. Others, including climate change and the threat posed by cosmic impacts, have received attention by scientists only in the past few decades. The belated recognition of these threats is a consequence of the long time scales between destructive events, not an indication that they are any less lethal than those that have long been known. Indeed, climate change and cosmic impacts are distinguished by their potential to devastate civilization as we know it. It therefore behooves us to systematically assess the magnitude of these threats.

Climate can be altered by modifications in global volcanism, solar output, or the influx of interplanetary dust. Both deterministic and chaotic celestial mechanics introduce variable solar insolation, and society's contaminants affect the atmosphere's response. The interactions among these influences are so complicated that they are not yet fully understood. The atmospheres of Venus and Mars, for example, evolved such that they differ radically from Earth's atmosphere. To learn the reasons for these differences is a central motivation for the SSE Survey's support of a vigorous Mars program and of in situ investigations of Venus. In the latter case, temperatures vastly higher than those on Earth result from a runaway greenhouse effect of a magnitude seemingly incommensurate with Venus's slightly smaller orbital radius. Mars's thin carbon dioxide atmosphere represents the other extreme, in which temperatures are low and a significant fraction of the atmosphere lies buried as ice within the regolith and upper crust. These "end members" of terrestrial atmospheric evolution nicely bracket the thankfully clement climate prevailing on Earth.

The atmospheric, geological, and evolutionary effects of cosmic impact have become apparent only since the early 1980s, when the likely cause of the Cretaceous-Tertiary extinction was first associated with the impact of a 10-km asteroid.[1] Colliding asteroids and comets of even much smaller diameter deliver enormous kinetic energy with possibly deadly consequences ranging from local to global. At Congress's direction, the National Aeronautics and Space Administration (NASA) has supported a ground-based program to identify 90 percent of the near-Earth objects (NEOs) larger than 1 km in diameter by 2008. The task is now about half complete, although the best simulations of the current survey strategies predict that this goal will not be met for many decades.[2]

Kilometer-sized impactors would be globally devastating, and even the much more common smaller projectiles could wreak unimaginable local havoc in populated areas. The high-altitude explosion of an 80-m-diameter body above Tunguska, Siberia, in 1908 felled trees over a 2,000-km^2 blast zone, and would have been sufficient to flatten a large city. Assessment of the NEO population down to 300-m scales, as part of an organized inventory of the small bodies of the solar system, was recognized as a high priority for NASA's Solar System Exploration program in the most recent astronomy and astrophysics decadal survey.[3] We also need refined physical observations of these threatening objects in order to determine their physical properties and estimate their kinetic energy.

Once human exploration of the solar system is renewed, and especially as soon as lengthy missions begin, knowledge of the available extraterrestrial resources will be imperative. Preliminary studies have identified sites where specific resources may be located and have suggested the means to extract these valuable minerals and compounds. Examples include hydrogen "lodes" on the Moon and metallic ore veins through asteroids as well as water and ice reservoirs in the martian regolith.

In summary, solar system exploration has become particularly compelling today because now, nearly half a century after space vehicles first left Earth's gravitational grip, we have finally reached the point where the answers to profound motivational questions seem within our grasp.

SOLAR SYSTEM EXPLORATION: AN INTERNATIONAL ENTERPRISE

The exploration of the solar system is a global endeavor involving scientists, engineers, managers, politicians, and others from many nations, sometimes working together and sometimes in healthy competition, to open new frontiers of knowledge about the solar system. Across the world the program enjoys wide public support, motivated as much by the possible human colonization of the solar system as by specific scientific questions.

Since its inception, solar system exploration has been an international venture. But the early post-Sputnik days of flyby missions and even in situ exploration coincided with the Cold War years, engendering fierce competition between the United States and the Soviet Union. Even during that era the two rivals occasionally cooperated—for example, in the exchange of lunar samples collected by the Apollo and Luna programs as well as in collaborations for the analysis of solar wind interactions with comets. More recently, international collaborative efforts have grown, leading to various programs that have significantly enhanced mission capabilities and scientific returns. International involvement has covered many different aspects of exploration, from individual scientific collaborations and data exchanges to joint major undertakings (e.g., the Galileo, Cassini-Huygens, and Rosetta missions). International collaborations could be strengthened by ensuring strong participation by non-U.S. members on science definition teams for specific projects, as is done for some missions, and by giving further consideration to standing groups such as the International Mars Exploration Working Group.

Some future endeavors are so vast in scope or so difficult (e.g., sample return from Mars) that no single nation is prepared to allocate the resources necessary to accomplish them alone. It would be advantageous to the Solar System Exploration program for NASA to encourage and facilitate such joint ventures so as to allow them to flourish in the future.

The theme of international cooperation appears often in Part Two of this report and **the SSE Survey recommends that NASA encourage and continue to pursue cooperative programs with other nations.**

Nevertheless, primarily because of constraints on its scope, this report focuses only on the status and future of solar system exploration programs in the United States. The SSE Survey attempts to identify where major international cooperation is advisable but in its discussion of future strategy does not consider in any depth the remarkable and exciting plans of other agencies in the international community, nor does it consider the ramifications of international space programs.[4,5]

MODIFYING THE GOALS OF SOLAR SYSTEM EXPLORATION

Solar system exploration has been pursued in the United States for fully four decades. During most of that time, the scientific goals of NASA's Solar System Exploration program have remained quite stable, with their relative importance gradually evolving over time. The SSE Survey largely reaffirms the statement of scientific goals made in the Space Studies Board's last major survey of the planetary sciences,[6] but with the following modifications. First, the SSE Survey includes the search for the existence of life, either past or present, beyond Earth, and second, the Survey seeks to incorporate the development of detailed knowledge of Earth's immediate space environment in order to understand any potential hazards to our home planet.

The objectives of solar system exploration, then, become these:

- Determine if environments capable of sustaining life exist or have ever existed beyond Earth, what parameters constrain its occurrence, how life developed in the solar system, whether life exists or may have existed beyond Earth, and in what ways life modifies planetary environments;
- Understand how physical and chemical processes determine the main characteristics of solar system bodies and their environments, thereby illuminating the workings of Earth;
- Learn how the Sun's retinue of planets and minor bodies originated and evolved;
- Explore the terrestrial space environment to discover what potential hazards to Earth may exist; and
- Discover how the simple, basic laws of physics and chemistry can lead to the diverse phenomena observed in complex systems.

In the early years of NASA's Solar System Exploration program, especially during the period surrounding the Apollo explorations of the Moon, space policy was dominated by political goals: for example, President Kennedy's decision to place a human on the Moon by the end of the 1960s. Then and for many years to follow, robotic spacecraft were dispatched on scientific missions designed to simply discover the general nature of the solar system. This era of initial reconnaissance began in the 1960s and encompassed the Mariner missions to Venus, Mercury, and Mars and the Pioneer and Voyager explorations of planets and satellites in the outer solar system, and concluded in the 1990s with the Galileo, NEAR, and Deep Space 1 explorations of asteroids and comets.

Today, as a result, only the myriad newly discovered objects within the Kuiper Belt, including the Pluto-Charon system and related bodies such as Centaurs and Trojans, remain entirely unexplored by spacecraft.

A new phase of exploration began with the Viking missions to Mars (launched in 1975), the Magellan mission to Venus (launched in 1989), the Galileo mission to Jupiter and its satellites (launched in 1989), and the Cassini-Huygens mission now en route to Saturn and Titan. The goals of these missions reflected a new focus: more intensive exploration, including the landing and the emplacement of atmospheric probes. The science objectives advanced from first-order reconnaissance to detailed chemical and physical explorations of selected objects to determine their origins and to ascertain the processes that shaped their identities, and, for the first time, to search for life beyond Earth.

Today, we find the focus sharpening further, following the 1996 announcement that a meteorite, ALH84001, which likely originated on Mars, showed evidence, albeit of a highly controversial nature, of possible past life activity on that planet.[7] The claims concerning ALH84001, though questioned from the outset and now generally discredited, triggered a series of subsequent scientific, political, and programmatic initiatives that have had a very positive impact on solar system exploration. Prime among the benefits was the so called Origins enhancement to NASA's budget for FY 1998. Since then, the Mars component of NASA's Solar System Exploration program has enjoyed increased support and has developed according to strategies sometimes termed "Seek, in situ, and sample" and "Follow the water." These strategies are ultimately aimed at determining the conditions of Mars and whether life ever arose on that planet. The program of geological, geochemical, and geophysical explorations now under way is preparatory to the future return of material samples from Mars to terrestrial laboratories and is directed in part to resolve these questions.

Other observations have initiated this redirection in mission focus. For example, magnetic-field measurements and images from the Galileo orbiter in the late 1990s strongly suggest that a 100-km-deep global ocean of water, a possible abode of life, may currently reside below the icy crust of the jovian satellite Europa. Similar magnetic characteristics also indicate possible subsurface oceans within Ganymede and Callisto. These measurements have prompted NASA to study intensively an orbital mission to begin detailed probing of Europa's putative ocean. Simultaneously, in the crucial area of Earth-based studies, NASA instituted the well-funded Astrobiology program in the late 1990s. Research funded through NASA's preexisting Exobiology program resulted in the discovery of the three-domain, phylogenetic tree of life and revealed the evolutionary significance of organisms from environments previously thought to be incompatible with carbon-based life (e.g., hot springs and deep-sea vents).[8] That such organisms—extremophiles—occur on Earth wherever liquid water exists has expanded our notion of what constitutes a habitable world. This and other related discoveries prompted NASA's increased commitment to the search for life elsewhere in the solar system as a significant aspect of its exploration strategy.

Astrobiology—as does its intellectual precursor, exobiology—has a reciprocal relationship with solar system exploration. It provides guidance for mission design and a framework for interpreting new discoveries. Originally concerned with cataloging observations of phenomena that might be characteristic of life found in regions beyond Earth's atmosphere,[9] astrobiologists now study all processes that are associated with the formation, population, and extinction of habitable worlds.[10,11] The intellectual goals of this scientific discipline embrace three questions: How does life begin and develop? Does life exist elsewhere in the universe? What is the future of life on Earth and beyond?

Astrobiology's multidisciplinary thrust provides an integrating theme, bringing together a substantial fraction of the issues in solar system exploration under the common thread of understanding planetary habitability. Rather than merely addressing the distribution of life in the universe, astrobiologists are concerned with clarifying the dynamical past of the solar system that led to terrestrial planets and their satellites, the interplanetary transport mechanisms responsible for cross-solar-system redistribution, the history of volatiles and organics, the processes (atmospheric and surficial) that affect the evolution of volatiles and the formation of habitable planets, prebiotic chemistry and the emergence of life, the influence of impactors on the survival of living systems, and all processes that lead to loss of the habitability of solar system objects. Astrobiology has both empirical and experimental dimensions. It seeks a historical accounting of the evolutionary processes that guided solar system formation and the emergence of life on Earth. At the same time, astrobiology aspires to understand, through multidisciplinary experimentation, the theoretical basis of how and why these processes occur.

Astrobiology as a theme provides a scientific organizational structure that integrates a wide subset of solar system issues and questions that span the origins, evolution, and extinction of life. This theme allows nonexperts to grasp the connections between different component disciplines within planetary science and to do so in a way that most people will appreciate as addressing core themes in human thought. Astrobiology and its connections to space science (and solar system exploration in particular) are the primary means by which NASA tries to implement one of its prime objectives—understanding life's origins and its distribution in the universe.

Astrobiology also has some priorities that are intimately connected to and rely on planetary exploration. Scientific objectives mentioned later in this survey of solar system exploration that directly address key questions in astrobiology include the following:

- Determination of the composition, abundance, and distribution of organic materials in the solar system;
- Exploration of both the potential oceans where life might emerge and the radiation environment at the surface and near-surface regions of Europa and the other Galilean satellites;
- Detailed determination of the elemental, chemical, isotopic, and mineralogical composition of the surfaces and upper crusts of planets and satellites (including Mars, outer solar system satellites, and icy objects);
- Investigation of the nature of atmospheric evolution and geochemistry on Venus and Mars relative to that on Earth in order to understand the potential for planetary evolution into habitable versus sterile worlds;
- Description of the detailed history of impactors and their potential influence on the evolution of terrestrial biospheres; and
- Further exploration of Mars, including a detailed search for subsurface liquid water and possible ground-ice inventories, full determination of surface mineralogy, and assessment of possible spatial and temporal juxtaposition of liquid water and sources of energy that could support life.

NASA's Astrobiology program has become a fundamental part of the solar system exploration strategy. **The SSE Survey encourages NASA to continue the integration of astrobiology science objectives with those of other space-science disciplines. Astrobiological expertise should be called upon when identifying optimal mission strategies and design requirements for flight-qualified instruments that will address key questions in astrobiology and planetary science.**

The goals for solar system exploration advocated in this report are sufficiently comprehensive to be resilient to the kind of minor readjustments in focus just described. In a real sense, today's objectives, as rephrased at the beginning of this section, define what the SSE Survey believes solar system exploration is and should be. However, as discoveries are made, changes in emphasis among these thrusts are inevitable. Today, solar system exploration focuses predominantly on questions of habitability and the possible existence of extraterrestrial life. The President's 2003 budget, for example, proposes the New Frontiers program with precisely this overarching goal.[12] The SSE Survey interprets this objective broadly, since any plan to address the possible existence of extraterrestrial life presupposes an extensive investigation of planetary evolution and of the planetary conditions that are conducive to the development of living organisms. In this regard, it should be noted that some of the primary goals of astrobiology can be met most efficiently through understanding particular planetary bodies and the way that they fit into the broad context of the solar system as a whole.

It is difficult to judge with confidence the degree to which the goals of the international community have altered to parallel those of the United States. Certainly the Soviet program shared the same early emphasis on lunar exploration and sample return, but it was originally more clearly focused on robotic investigations and techniques. Soviet reconnaissance missions to Venus and Mars quickly followed, with significant successes in robotic landings on the hellish surface of Venus.

Reconnaissance of the solar system by other nations experienced great success in the 1980s, with the first explorations of Comet Halley's nucleus by the Vega, Giotto, Suisei, and Sakigake spacecraft. Together, these missions filled in an almost-empty paradigm with unexpected details concerning the nature of cometary activity and the composition of cometary solids. Today the international community is mounting major geophysical and geochemical explorations of the Moon, Mars, comets, and asteroids with the Selene, Nozomi, Mars Express, Beagle 2, Smart 1, Rosetta, and MUSES-C missions.

RECENT ACHIEVEMENTS IN SOLAR SYSTEM EXPLORATION AND RELATED FIELDS

Our perceptions of our planetary neighborhood have been overturned since the space age dawned. Dots of light in the night sky have been transformed into exquisite worlds displaying bizarre phenomena—softly hued vortices swirling past Jupiter's Red Spot, enormous canyons and outflow washes crisscrossing Mars, or austerely beautiful rings encircling each of the giant planets.

The remarkable diversity and activity of the solar system were totally unexpected by planetary scientists and were forecast by just a few others, but mostly as science fiction. To illustrate the vitality of the discipline, it may be instructive to mention just a few of the findings since the publication of the last solar system survey less than a decade ago.[13] Most of these new understandings lead to additional questions.

To identify the most important discoveries of the past decade, the SSE Survey's Steering Group relied upon community input to its panels (see Part One), along with independent surveys of the scientific community and the public (see Appendixes C and D). Box 6.1 lists the most significant additions to our understanding of the solar system, while Box 6.2 outlines a half dozen of the most vexing and mysterious issues facing planetary scientists today.

A plethora of extrasolar giant planets, whose orbital characteristics have startled theoreticians, have been discovered elsewhere in our galaxy. Indeed, perhaps 5 percent of main sequence stars have massive companions, but the ubiquity of terrestrial-like planets remains unknown. Simultaneously, dust disks have been found to commonly enshroud most young stars, and even some aged ones. These observations suggest that the formation of planets is not unusual.

Researchers now wish to use ground-based telescopes and future spacecraft, such as Kepler and the Space Interferometry Mission (SIM), to observe a statistical sample of extrasolar planets in order to better understand the origin and evolution of planetary systems. Such studies will eventually be extended to the search for Earth-like planets and, ultimately, will characterize their atmospheres and their habitability with advanced orbital observatories such as the proposed Terrestrial Planet Finder (TPF) mission. Our understanding will be improved if we use the properties of our own gas giants to calibrate the processes exhibited in other planetary systems and to obtain clues to the primordial composition of the solar system.

Since the first Kuiper Belt object was detected in 1992, hundreds more have been sighted, disclosing a large extension to the solar system beyond Neptune. Similar structures are inferred to explain the oldest of the extrasolar disks. We are in the midst of compiling the first catalog of this territory that circumscribes the outer solar system so as to unravel its morphology and makeup and to allow an understanding of its relationship to the formation of the solar system.

BOX 6.1
Recent Significant Discoveries in Solar System Exploration

- Giant extrasolar planets and dust disks around many stars
- The Kuiper Belt, a large extension of the solar system beyond Neptune
- Possible subsurface oceans within the icy Galilean satellites
- Evidence that Mars might have been hospitable to life in its past
- Disputed evidence for life on ancient Mars in the meteorite ALH84001[1]
- Identification of the Chixulub crater on Earth and observations of the impacts of giant fragments of Comet Shoemaker-Levy 9 on Jupiter

[1]Included for its very positive, long-term policy implications rather than for the validity of the original claims.

BOX 6.2
Six Continuing Mysteries About the Solar System

- *The diversity of bodies in the solar system.* There are several distinct classes of objects now recognized in the solar system, including the terrestrial planets, the gas giants (Jupiter and Saturn), the ice giants (Uranus and Neptune), and the Kuiper Belt objects (including Pluto). Is this a common feature of other planetary systems, and, if so, what is its cause?
- *The sharp contrast between Earth and Venus.* Although similar in size, mass, composition, and solar distance, Venus is hellish while Earth has life. Did Venus once have an ocean's worth of water? Is the uniqueness of Earth's Moon a factor? What basic factors control climate?
- *The potential habitability of Mars.* Mars, the most Earth-like planet, is on the threshold of habitability. It has undergone significant changes over time, including massive climatic shifts, enormous magmatic events, the escape of volatiles, and the development and subsequent loss of a strong magnetic field. When and how did these changes occur? How did the complex interactions between various environmental factors affect prebiotic conditions and the possible origin, evolution, and survival of life?
- *The effect that the asteroids and comets have on Earth.* The small, wandering bodies of the solar system may determine the fate of Earth. What role have asteroids and comets played in delivering volatiles to Earth or in punctuating evolution through globally devastating impacts? Do these objects determine our ultimate fate?
- *Distant worlds of fire and ice, and possible life.* Activity abounds on the satellites of the outer solar system, from Io's fiery volcanoes to Triton's frigid geysers. What is the role of tidal heating? How many of the large icy moons hide subsurface oceans? Are these oceans habitable?
- *Nature of the Kuiper Belt and its myriad objects.* What is the diversity of compositions among Kuiper Belt objects? How many Pluto-sized or larger Kuiper Belt objects exist? What is the relationship of Kuiper Belt objects to comets, Trojans, and Centaurs? And, where does the Kuiper Belt end?

The discovery of possible subsurface oceans on several Galilean satellites has led to the recognition of a possible but unexpected abode for life beyond Earth. The current goals are to identify and determine the extent of any such subsurface ocean. Simultaneously we must rethink our ideas of habitable zones.

Evidence continues to accumulate indicating that water flowed on or near the martian surface in geologically recent times. This, together with indications of subsurface reservoirs of ice and geological activity, suggests that the Red Planet might have been hospitable to life in its past. We now should continue to document the nature of any past habitable climate and to characterize the extent of subsurface water and ice to see how closely they approach the surface. In situ investigations for water and evidence of past or present life should also be conducted.

Acceptance of the possibility of extraterrestrial life has progressed markedly during the past decade. Illustrating this are claims made for extinct life forms in the ancient martian meteorite ALH84001. While these claims have been sharply disputed, the debate has been on scientific terms and has concerned the validity of the evidence. This new perception in part also results from the concurrent discovery of terrestrial extremophiles. This discovery encourages a continuing search for and examination of other martian meteorites for biological evidence. Also, samples of known provenance should be returned to Earth for their mineralogical and isotopic characterization and ultimately to verify any in situ biological evidence.

As a final example of the advances made in the last decade, scientists in the 1990s realized the crucial role of impacts in altering life's path once they identified the Chixulub crater in the Yucatan as responsible for the Cretaceous-Tertiary (K-T) extinctions on Earth. In the same period, the pummeling of Jupiter with the remnants of Comet Shoemaker-Levy 9 reminded us all of the ubiquitous and continuing role of collisions in shaping planetary bodies. As a result of these findings, we now recognize that we must survey the skies for threatening

NEOs and maintain a watch for potential impactors. To make these identifications useful, we also need to determine relevant physical and compositional properties of potential impactors, including comets.

THE RELATIONSHIP OF SOLAR SYSTEM EXPLORATION TO SCIENCE AND ENGINEERING DISCIPLINES

The success of a solar system exploration mission relies crucially on the well-being of a wide range of scientific investigations and effective engineering. To be of value, missions not only must reach their targets quickly and with adequate power and stability, but also must produce significant scientific data that address the scientific goals noted previously. Scientific investigations are usually drawn from various established disciplines, including planetary science, geophysics, geology, atmospheric physics, cosmochemistry, fluid mechanics, meteoritics, space plasma physics, astrobiology, and aeronomy—to name but a few.

This point is made to emphasize the wide array of scientific disciplines that are informed by solar system exploration. The interaction between the disciplines and missions flows both ways—solar system exploration missions rely on a healthy scientific community for support and direction, and the value of the missions is dramatically enhanced by research that capitalizes on returned data. The nation's solar system exploration enterprise is driven by the high-level public goals outlined above, but it is not possible without strong support for the scientific and engineering backbone of the program. This support is currently lacking in several areas, which are detailed later in this report.

THE SOLAR SYSTEM EXPLORATION PROGRAM AT NASA: INTERRELATIONSHIPS

Relationship with Other Science Programs

Solar system exploration is currently overseen by two components of NASA's Office of Space Science (OSS): the Mars Exploration Program (MEP) office and the Solar System Exploration Division. This dual responsibility is recent and was apparently imposed to ensure that the exploration of Mars could progress at as rapid a pace as possible without being fettered by any problems that might arise in the more general program. The Solar System Exploration program is strongly coupled scientifically to other separately managed programs in NASA. Within the OSS, the strongest scientific and programmatic bonds are to the Sun-Earth Connections Division and the Astronomy and Physics Division.

The Sun-Earth Connections (SEC) Division sponsors research in solar and space physics with particular emphasis, as its name implies, on the Sun's effects on the terrestrial space environment. However, space physics research is not only concerned with solar-terrestrial relations but also encompasses study of the space environments of other solar system bodies. SEC strategic planning documents thus typically include missions to investigate planetary magnetospheres, ionospheres, and upper atmospheres.[14] A major thrust in the Sun-Earth Connections Division is the Living With a Star program—its purpose is to understand these Sun-Earth connections for very practical applications. This program overlaps with planetary science by aiming to help unravel how planets interact with solar insolation and the heliosphere, in order to understand the past and future climate and the gaseous and plasma environments of one very well studied planet.

The astronomy and astrophysics flight program conducted by the Astronomy and Physics Division is managed as two separate thematic groups, Structure and Evolution of the Universe and Astronomical Search for Origins. Roughly speaking, the former's activities are mostly devoted to high-energy astrophysics, whereas the latter's activities are devoted to less-energetic phenomena that are more relevant to the interests of solar system exploration, but not exclusively so. Planetary science has benefited enormously from Astronomical Search for Origins missions such as the Hubble Space Telescope (HST), and it expects more discoveries from the Space Infrared Telescope Facility (SIRTF), the Stratospheric Observatory for Infrared Astronomy (SOFIA), and other future space observatories (see below). Future Origins missions such as SIM and TPF are essential to extending planetary exploration beyond our own solar system, searching for other planetary systems, and then mounting spectroscopic investigations of extrasolar planets for evidence of biospheres. We see here examples of the strong interrelationship between studies relating to solar system exploration and astronomical origins. One provides a very detailed look at one example of planetary formation and evolution, while the other provides many examples of a wide variety of systems with different structures and at different stages of evolution.

Planetary science also has strong scientific links to NASA's Office of Earth Science (OES). Earth is the most intensely studied planet from space. Hence the science and observational techniques developed in OES are vital for the continuing development of planetary science and observations. The major thrust in OES is the Global Change program, from which planetary science will gain an understanding of Earth as a terrestrial planet among the four inner planets and will obtain data essential to understanding the origin and evolution of a terrestrial planetary biosphere.

Studies of the atmosphere and plasma environment of solar system bodies have been an integral part of the general solar system exploration effort since the launch of Mariner 2 in 1962 and are traditionally supported by NASA's Solar System Exploration program. Historically, some small but very important funding has also come from NASA's space physics activities and the National Science Foundation's astronomy and atmospheric science programs. This organizational arrangement made sense in the past and will continue to do so in the future, especially for in situ studies, because spacecraft traveling to various solar system bodies can and should carry a wide range of instrumentation. Examples of such successful undertakings are the Voyagers and the Galileo and Cassini orbital missions, as well as smaller ones such as Pioneer Venus. Comparative aeronomy and magnetosphere studies allow the knowledge of basic physical processes acquired through the study of the geospace environment to be applied to other solar system objects and afford a critically important opportunity to test our understanding of these processes by observing how they operate in other settings. Moreover, not only are there important connections between space physics and planetary science with regard to scientific themes relevant to both disciplines, but the instrumentation used in terrestrial space physics research and that used in solar system exploration also frequently have a common heritage.

Given the crosscutting interests among solar system exploration and terrestrial aeronomy and space physics studies, it is not surprising that the Space Studies Board's concurrent Solar and Space Physics Survey Committee also addresses some aspects of solar system exploration.[c] However, the nature and relative timing of these two somewhat parallel NRC studies did not permit as much direct coordination as would have been wished. Therefore, the recommendations associated with solar system exploration from these studies may advocate some different exploration strategies and priorities. These differences can and should be easy to resolve within the OSS. The excellent past cooperation between the different components of the OSS and among the scientific communities has encouraged and led to major advances in the field (e.g., the putative discovery of an ocean at Europa by magnetic-field observations) as well as exploration efficiencies. The SSE Survey strongly encourages the continuation of this cooperative exploration strategy.

Relationship with the Human Exploration Program

The Solar System Exploration program currently has no strong scientific or programmatic ties to the human spaceflight activities conducted by NASA's Office of Space Flight (OSF), although strong interactions occurred during the Apollo program.[15] The planetary program does, however, rely on the OSF for the procurement of launch services. The major thrust in the OSF is the construction of the International Space Station (ISS), with which no obvious connection with planetary exploration exists other than the potential of the ISS to serve as a future transportation node to the planets for both humans and robots.

Eventually there must be a strong coupling between robotic and human space exploration. Scientific exploration of the solar system and the scientific utilization of the space environment provide the impetus for human

[c]In its moderate program category, for example, the Solar and Space Physics Survey Committee assigned high priority to a Jupiter Polar Mission, a dedicated space physics mission to study high-latitude electrodynamic coupling between Jupiter's ionosphere and magnetosphere.

exploration beyond Earth orbit, and they are a prerequisite for sending humans to other worlds.[16] Robotic missions, for example, will collect the data necessary for sending astronauts to Mars and back safely.[17] These precursor experiments and measurements would provide information on target selection, surface physics and chemistry, the threat that high-energy particles pose during travel, and so on.[18] In the long run, human exploration of our celestial neighborhood is a driving force in its own right, but it will also furnish opportunities for significant science accomplishments.

The SSE Survey is not convinced that human exploration beyond Earth orbit will raise major issues for the planetary science community during the coming decade. Nevertheless, it would be a mistake for scientists to dismiss out-of-hand those individuals aspiring to return to the Moon, to walk on Mars, or to exploit the resources of near-Earth objects. This is true if for no other reason than to avoid future conflicts over limited resources. A prime lesson from recent human exploration activities is that prior planning by scientists might preclude a "shotgun wedding" sometime in the future.

ISSUES REGARDING THE INFRASTRUCTURE OF THE SOLAR SYSTEM EXPLORATION PROGRAM

It is far beyond the scope of this survey to give an exhaustive analysis of the current performance of the entire scientific and programmatic infrastructure of U.S. solar system exploration activities. However, the SSE Survey became aware of several controversial issues concerning the way this infrastructure currently operates. It is hoped that raising these issues will help the audience for this report recognize the "big picture" of how solar system exploration is practiced today; this identification may also aid in rectifying some of its deficiencies.

Research and Analysis Programs

It is largely through the work supported by research and analysis (R&A) programs within the Office of Space Science that the data returned by flight missions are converted into new understanding, advancing the boundaries of what is known. The research supported by these programs also creates the knowledge necessary to plan the scientific scope of future missions. Covered under this line item are basic theory, modeling studies, laboratory experiments, ground-based observations, long-term data analysis, and comparative investigations. The funds distributed by these programs support investigators at academic institutions, federal laboratories, nonprofit organizations, and industrial corporations. R&A furnishes the context in which the results from missions can be correctly interpreted. Furthermore, active R&A programs are a prime breeding ground for principal investigators and team members of forthcoming flight missions.

Healthy R&A programs are of paramount importance and constitute a necessary precondition for effective missions. This conclusion has been stated repeatedly and forcefully before,[19] and it is shared by NASA's Office of Space Science. The three R&A clusters (i.e., Origin and Evolution of Solar System Bodies, Planetary Systems Science, and Astrobiology and Planetary Instrumentation) most closely associated with solar system exploration were supported at the level of $96 million in FY 1999. This level is now expected to rise at about 3 percent per year above the underlying inflation rate for several years. This proposed rise is included in the President's FY 2003 budget.[20] Nevertheless, serious problems remain with these programs. The ratio of submitted to funded proposals is typically 3 to 1, which—the SSE Survey believes—is too high, since at this rate new proposals can rarely be funded. Also, the availability of authorized funds is often subject to delays and, in recent times, the value of the median grant has fallen to below $50,000 per annum, a level generally too small to support a researcher or a tuition-paid graduate student.[21]

The SSE Survey agrees with the Space Studies Board recommendation that NASA should routinely examine the size and number of grants to ensure that the grant sizes are adequate to achieve the proposed research.[22] The Survey supports the budgetary proposals that would steadily expand solar system exploration R&A programs. **The SSE Survey recommends an increase over the decade 2003-2013 in the funding for fundamental research and analysis programs at a rate above inflation to a level that is consistent with the augmented number of missions, amount of data, and diversity of objects studied.**

R&A programs are not currently—and in the opinion of the SSE Survey should not be—tied to specific mission goals. Thus, individual research projects do not correspond to particular missions. Nevertheless, as the breadth and depth of the space exploration missions increase, the R&A programs should expand and be redirected correspondingly. Therefore, in the broadest sense, R&A programs must be responsive to the current mission opportunities even if they are not rigidly coupled to them.

Previous NRC studies have shown that, after a serious decline in the early to mid-1990s,[23] the overall funding for R&A programs in NASA's Office of Space Science has, in recent years, climbed to approximately 20 percent of the overall flight-mission budget.[24] Figures supplied by NASA's Solar System Exploration program show that the corresponding value for planetary activities is closer to 25 percent and is projected to stay at about this level for the next several years. The SSE Survey believes that this is an appropriate allocation of resources.

Creation of Intellectual Capital

Finally, to maintain and enhance the scientific productivity of the entire solar system exploration enterprise and to ensure the creation of new intellectual capital of the highest quality in the field, **the SSE Survey recommends the initiation of a program of Planetary Fellows, that is, a postdoctoral program analogous to the Hubble and Chandra fellowships, which have done so much to nurture the next generation of astronomers and astrophysicists.** The purpose of this program would be to allow the brightest young investigators the opportunity to develop independent research programs during their most creative years. These would be prestigious, multiyear fellowships, based solely on highly competitive research proposals and tenable at any U.S. institution.

TELESCOPE FACILITIES: AN ESSENTIAL ELEMENT OF AN INTEGRATED SOLAR SYSTEM STRATEGY

Ground-based Telescopes

Two major scientific findings of the past decade, according to a ranking by planetary scientists (see Box 6.1 and Appendix C), were made using ground-based telescopes. The discoveries of extrasolar planets and of the Kuiper Belt have had an undeniable impact on our perception of our surrounding solar system and thus on the optimal strategies for future spacecraft missions.

Except for the major planets out to and including Saturn, all of the bodies of the solar system, including all those visited by spacecraft, were discovered by ground-based telescopes. Spacecraft provide invaluable in situ data on objects that were first identified from the ground. Utilization of the enormous discovery potential of ground-based telescopes is an essential part of an integrated strategy for solar system exploration.

Telescopes are vital in several ways. First, they provide the targets to which flight missions can later be directed. A prime example is that of the Kuiper Belt, which emerged in the 1990s as a vast, unexplored (and previously only postulated) "third domain" of the solar system beyond the realms of the terrestrial and giant planets. Even our yet-preliminary understanding of the dynamics of the objects beyond Neptune has led to wide acceptance of the outward migration of proto-Neptune at the solar system's dawn.

Another example of a "found" population is that of the near-Earth objects, which are now understood to pose a potential impact threat to Earth, but also could be exploitable both for sample return and as springboards for future human exploration missions.[25] NEOs present such attractive targets for spacecraft missions because some of them require the expenditure of less energy for rendezvous than that needed for any other planetary bodies. For this reason, some have argued that, in the long term, NEOs may become economically attractive sources of minerals and metals that are comparatively inaccessible on Earth.

NEOs include both asteroids and dormant comets. While the existence of this population has been recognized for many decades, systematic surveys conducted over the past 5 years have managed to discover only about two-thirds of the NEOs with sizes greater than 1 km that are thought to exist. It is also just within the past decade that the terrestrial hazard from these bodies has been widely accepted.

A second way in which ground-based telescopes are important is that they provide ongoing support for spacecraft missions, both before and after the mission. As an example, NASA's Infrared Telescope Facility's (IRTF's) thermal imaging of the Galileo probe's entry site showed that the probe descended through an atypical "hot spot" in Jupiter's cloud tops. This knowledge has proven crucial to the scientific interpretation of the compositional data returned by the probe, and in particular in explaining why the measured water abundances were unexpectedly low. Similarly, the success of the Stardust and Deep Impact missions crucially depends upon ongoing ground-based characterization of their target comets. The mission-funded studies of the Deep Impact target, for example, have greatly reduced the volume of parameter space that must be considered by the mission designers. Moreover, events associated with the impact into the target will be observed by telescopes around the world, complementing observations made by the spacecraft's instruments. Another good example of mission support concerns ground-based studies of the physical characteristics of the asteroids Gaspra and Ida prior to the encounters of the Galileo spacecraft.

In a much broader sense, Earth-based observations provide the context for mission results. Earth-based studies alone have allowed us to develop taxonomic systems for asteroids and comets. It is through these classification schemes that it is possible, for example, to expand the interpretation of results from the Near-Earth Asteroid Rendezvous (NEAR) mission's studies of Eros to other similar asteroids.

Ground-based planetary radar facilities at Arecibo, Puerto Rico, and Goldstone, California, are used for detailed, physical characterization of many different bodies in the solar system. Much of the initial reconnaissance of Venus's surface was conducted with the Arecibo telescope, providing valuable input to and context for subsequent radar studies undertaken by the Magellan mission. The same facility has also identified highly reflective areas on Mercury thought to be due to ice located in permanently shadowed craters in the planet's polar regions. Similarly, the Goldstone facility has been used to study the bulk surface properties of the icy Galilean satellites. Both facilities have been employed to "Doppler-image" several near-Earth asteroids, providing information on their shape, surface roughness, composition, and spin state, in addition to dramatically improving measurements of their orbits.

Although important to solar system exploration, planetary radar studies at both Arecibo and Goldstone are highly leveraged activities. Roughly 90 percent of the Arecibo budget is provided by NSF to support general radio astronomy studies. Similarly, the bulk of the Goldstone funding arises from its role as a communications hub in NASA's Deep Space Network (DSN).

NASA continues to play a major role in supporting the use of Earth-based optical telescopes for planetary studies. It funds the complete operations of the IRTF, a 3-m-diameter telescope located on Hawaii's Mauna Kea. In return for access to 50 percent of the observing time for non-solar-system observations, the NSF supports the development of IRTF's instrumentation. This telescope has provided vital data in support of flight missions (as described above) and will continue to do so. NASA currently purchases one-sixth of the observing time on the privately operated Keck 10-m telescopes. This time was purchased to test interferometric techniques in support of future spaceflight missions such as SIM and TPF. However, the fraction of the NASA time available for general solar system observations is rapidly shrinking as the Keck interferometers come online.

The SSE Survey recommends that NASA continue to support ground-based observatories for planetary science, including the planetary radar capability at the Arecibo Observatory in Puerto Rico and at the Deep Space Network's Goldstone facility in California, the Infrared Telescope Facility on Mauna Kea in Hawaii, and shares of cutting-edge telescopes such as the Keck telescopes on Mauna Kea, as long as they continue to be critical to missions and/or scientifically productive.

Interestingly, NASA has no systematic survey capability to discover the population distribution of the solar system bodies. To do this, NASA relies on research grants to individual observers who must gain access to their own facilities. The large NEOs are being efficiently discovered using small telescopes for which NASA provides instrumentation funding, but all the other solar system populations—for example, comets, Centaurs, satellites of the outer planets, and Kuiper Belt objects—are being characterized almost entirely using non-NASA facilities. This is a major deficiency, since a large-aperture survey telescope will be essential to support the flight-mission strategy (for example, by selecting and characterizing key targets of the mission) developed in Chapter 8, where the SSE Survey makes a strong related recommendation.

Space-Based Telescopes

Many significant discoveries in planetary science have come from Earth-orbiting telescopes operating at a variety of different wavelengths. These discoveries include the following:

- The unexpected detection of strong x-ray emissions from comets;
- Studies of jovian atmospheric chemistry based on HST observations of the impacts of Shoemaker-Levy 9 into Jupiter; and
- The discovery of a star's strong water emission that is best interpreted as the evaporation of icy bodies in the outer planetary system of that star.

The anticipated launch of SIRTF and the flights of SOFIA will provide additional superb tools for planetary science, particularly in determining absolute sizes and the surface reflectivity of numerous objects in the Kuiper Belt. The Long Duration Exposure Facility (LDEF) made major contributions to our understanding about the nature and provenance of interplanetary dust.

With the exception of the recently selected Kepler mission in the Discovery program, these orbiting telescopes have been built and operated under the auspices of NASA's nonplanetary programs. Indeed, because of the commonality of the tools used by planetary astronomers and their colleagues interested in stellar, galactic, and extragalactic phenomena, virtually every major astronomical mission that has flown has made some significant contribution to solar system exploration. The close coincidence between the instrumentation used by planetary and other astronomers makes it unnecessary for the SSE Survey to recommend a major Earth-orbiting telescope devoted exclusively to solar system studies. The Survey prefers to rely on the Discovery and, where appropriate, the Explorer lines to generate appropriate candidates. **It is noted, however, that using Earth-orbiting facilities for planetary observations imposes special constraints—notably the need to track moving targets—and the SSE Survey endorses the incorporation of this technically difficult but essential capability on all relevant astronomical telescopes.**

DATA ARCHIVING

The Planetary Data System (PDS) was developed to provide the archiving function through working scientists; in astrophysics, data archiving is provided by the operating entities for the Hubble Space Telescope and the other Great Observatories. The budgets for early Discovery missions (e.g., Lunar Prospector) and technology-demonstration activities (e.g., the Department of Defense's Clementine and NASA's Deep Space 1) made no provision for archival products. As a result, data from these missions have been very little analyzed. The recent success of the NEAR mission and its return of a huge volume of data—an order of magnitude more than when the mission was planned—have highlighted the importance of archiving as a separate activity within solar system exploration. These events have also illustrated many of the pitfalls in establishing an archive from a highly productive mission that was budgeted in the Discovery range. The risk exists that the scientific return from solar system exploration missions will be smaller than ideal as small, principal-investigator-led missions proliferate. Although it is too early to judge, it appears that the Mars program has already begun to ensure that archiving will be well handled.

At present, the PDS appears to have insufficient resources for the job it has been given. Moreover, only rarely is the PDS involved as a scientific partner at a mission's outset. By contrast, a new instrument for HST is developed with consideration for the pipeline processing and archiving from the outset. The PDS faces two distinct challenges in the immediate future—the diversity and number of missions on the one hand and the volume of data on the other. The interaction with many different missions is currently severely stressing the capability of the PDS. On the technological front, the Mars Reconnaissance Orbiter alone is projected to return at least 300 terabytes of data, a volume exceeding that of all the Great Observatories combined and presenting a major challenge to the PDS.

The increasing attention paid to archiving plans in the recent rounds of Discovery selections has been a step forward, as has the recent support by the Mars program, although the overall situation remains unsatisfactory. The SSE Survey notes, for example, that all Discovery proposals are required to budget 1 to 2 percent of their total cost for education and public outreach (E/PO), a valuable activity that is also highly leveraged with external resources. The total amount of money spent on preparing archival products by any mission is small compared to this, with the only leveraging being in the PDS budget, except in the special case of non-NASA missions for which there is large leveraging through the outside agency. This is the funding that is intended to provide the complete archival product, ready for use by the research community. The PDS is funded, at present, just to maintain suitable standards, to advise the missions, and to distribute the archival products, not to prepare them. The SSE Survey notes that in many cases the experience resident in the PDS could lead to more efficient preparation of archives if the PDS scientists were involved at the earliest stages. Furthermore, substantial community demand exists for access to the large databases of Earth-based data produced through NASA's R&A programs—data that are in general not archived with the PDS for lack of resources. Enhancements to either the PDS or mission budgets would enable data archiving.

The SSE Survey strongly encourages exploration of ways to accomplish the following:

- **Improve the early involvement of the PDS with missions;**
- **Increase the PDS budget and streamline its procedures, while not lowering standards or eliminating peer reviews, in order to deal with the data, perhaps considering the function to be funded at a fixed fraction, such as 1 percent of the mission development and operations budget in addition to a small base budget, to ensure that the PDS can cope with varying amounts of archiving; and**
- **Ensure that missions as well as R&A projects producing large data sets have adequate funding for proper archiving.**

DATA-ANALYSIS PROGRAMS

A crucial task in getting scientific value from solar system exploration missions is to properly organize and adequately fund strong data-analysis programs (DAPs). In order to maintain momentum, DAPs for the community should be ready to support investigators immediately upon the delivery of ready-to-use data to the PDS. This would allow continuity for investigators on short-lifetime missions that have reached their end, and it would allow outsiders sufficient monies to promptly attack scientific questions based on the data. In addition to providing adequate funding, several other procedural steps must occur.

Preliminary versions of the ultimate archival materials must be delivered regularly throughout the mission to avoid delays in the availability of final products at the mission's end. This requires the involvement of the PDS as a scientific partner very early in the mission. It also requires describing, in some detail, the content of the archive sufficiently before the DAP proposals are due, so that proposers can make sensible proposals before the data themselves become public. It also mandates that investigators be able to propose across missions when scientific questions clearly transcend individual missions. NASA's stated intent to merge—albeit a number of years in the future—the DAPs for individual Discovery program missions into a single DAP for the Discovery program appears to be a step in the right direction. This could allow a researcher, for example, to coherently analyze data from the several missions to comets, and, similarly, a Mars-data analysis program could allow a researcher to comparatively interpret data from several missions of the Mars program. The SSE Survey urges that these data-analysis programs be kept sufficiently flexible so that it is structurally easy to add a component for analyzing data from other sources, such as from technology missions—Deep Space 1 data from comet 19P/Borrelly (Figure 6.1) represents a current example—or from foreign missions archiving with the PDS (Mars Express, for example).

NASA's Great Observatories, most notably through the Space Telescope Science Institute (STScI), but also other Great Observatories, have conclusively demonstrated the great value of a uniform, readily accessible archive coupled with support for the analysis of the data by the original investigators as well as by others who use the archived data for research. Each scientific user of a Great Observatory is funded to analyze the data obtained in his or her program, and the mission itself maintains a long-term archive. Because the Great Observatories are

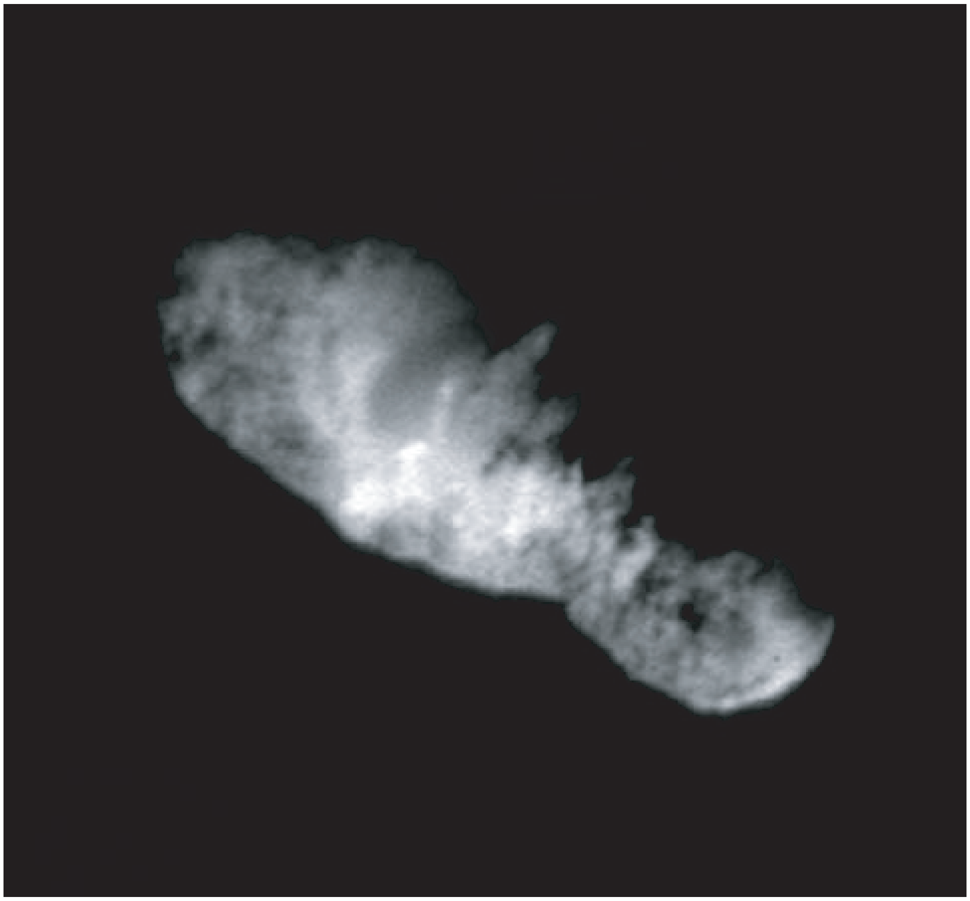

FIGURE 6.1 A close-up image of the nucleus of Comet 19P/Borrelly obtained by the Deep Space 1 spacecraft. Courtesy of NASA/JPL.

archiving large volumes of data from only a few instruments operated over a very long time, the archiving process becomes highly automated, and data appear in the archive typically within days of being obtained and long before they become publicly available. The data in the archive become public after a short period, varying from one observatory to another, but usually in no more than a year and sometimes immediately. Once data are in the public domain, other investigators can obtain funding to analyze them. Because the observing programs are publicly known even before the observations are carried out, investigators can plan ahead to apply for support to begin analysis immediately after the proprietary validation period has ended. STScI finds that the typical datum (one image or spectrum) is used in at least several separate investigations beyond that of the original observer. The accumulated download of data is many times larger than the total amount of data in the archive. This archival research has led to major discoveries and also has dramatically improved the planning for future missions.

The success of astrophysical archives has given birth to the National Virtual Observatory (NVO) initiative that should make the archives even more productive in the future.[26]

In solar system exploration, examples of the value of archives are diverse. The Geosciences Node of the Planetary Data System, for example, digitized the microfilm data from the Viking Labeled-release Experiment, thus enabling a new type of investigation searching for evidence of circadian rhythms in the data. The Small Bodies Node (SBN) provided archival interpretation of the Giotto trajectory for an investigator seeking to discover if the nucleus of Comet Grigg-Skjellerup is binary. The archives are also used extensively for planning future missions, all the way from the proposal stage through details of spacecraft and mission design. Investigators have written letters to the SBN highlighting how they have used the online database, particularly the database on Earth-based comparative data on comets and asteroids, to plan Discovery program proposals.

Solar system exploration missions operate entirely differently from the Great Observatories in many ways. The missions tend to be of fixed duration, and all but the Flagship missions usually have short lifetimes that make it impractical for the mission teams to either develop or maintain a long-term archive. The mission teams rarely have any expertise in archiving, and the data products from the teams often have grossly different formats with widely varying degrees of documentation. Furthermore, solar system exploration missions do not themselves include extensive, funded programs for guest observers, who effectively serve as user-reviewers of the archival pipeline. Data-analysis programs, established to allow research on the information returned from solar system exploration missions, have been hit-or-miss, often underfunded, of too short duration (e.g., the Venus Data-Analysis and Jupiter Data-Analysis programs), or nonexistent (e.g., the Galileo Europa and Millennium Mission extensions). On other occasions, funding is delayed to such an extent that research programs risk losing momentum (e.g., for the NEAR mission).

To obtain the maximum value from the scientific data returned from solar system exploration missions, it is essential to properly execute two intimately related activities. The first of these is to ensure that the archiving entity, the Planetary Data System, has the necessary resources for the job and is treated as an important scientific component of each mission from the outset. The second is to dramatically improve the data-analysis programs.

SAMPLE-RETURN FACILITIES

As part of NASA's Solar System Exploration program, samples will be returned from extraterrestrial bodies. Sample-return missions already under way include the Stardust and Genesis missions of NASA and the MUSES-C mission of Japan's Institute of Space and Astronautical Sciences (ISAS). Samples from these missions carry a planetary protection designation of "Unrestricted Earth Return."[27] They will be curated in dedicated facilities at the Johnson Space Center and distributed to qualified scientists for investigation. Samples returned from objects of biological interest (e.g., Mars and Europa) are subject to quarantine restrictions in a sample quarantine facility that can preserve the pristine nature of the samples and prevent back-contamination of Earth.[28]

Mars Quarantine Facility

Several NRC studies outline the containment requirements for samples returned from Mars.[29] With the exception of samples returned from Europa, there are few constraints on samples returned from small solar system objects.[30] The recent NRC report on the Mars Quarantine Facility (MQF) stresses that a minimum of 7 years will be required for the design, construction, and commissioning of the MQF, and that it must be operating up to 2 years prior to the arrival of martian samples. The purpose of the MQF is threefold: to sequester unaltered samples until biohazard testing is complete, to preserve the pristine nature of the samples, and to release samples deemed to be nonhazardous to a sample curation facility for allocation for further scientific study.

The technology required for containment and testing for pathogens is well developed. Biohazard assessment must also consider the potential ecological threats posed by returned samples. Sample containment must preserve the samples in a pristine condition, without inorganic and organic contamination. Technology for the preservation of samples similar to that used for lunar samples in the Lunar Curatorial Facility at the Johnson Space Center is well developed. However, the combination of biocontainment and preservation of samples in their pristine condition requires a unique design for the MQF that no currently existing facility provides. Another important design feature should be the potential for expansion, if early findings of definite evidence of extraterrestrial life warrant the need for all studies to be performed under containment.[31] The cost of building such a specialized quarantine facility needs to be investigated.

In addition to developing the technology to satisfy the design constraints for the MQF, it is also important to initiate a program to develop key research and analytical tools. These include, for example, the development of criteria for the following:

- Biohazard assessment,
- Definition of life and of standards for life detection that minimize sample size requirements,
- Sterilization of samples for potential early release, and
- Release from containment of samples deemed to be safe.

A vigorous research and analysis program must address these issues:

- Enhanced sterilization techniques that will minimally compromise the integrity of returned samples, and
- Highly sensitive techniques for life detection.

The sample-handling requirements for geochemical and biological investigations and for specific biohazard testing are not necessarily compatible. The NRC has recommended that an advisory committee oversee the design and construction of the MQF and that this group "will be ultimately responsible for the disposition and handling of samples in the MQF until they are judged to be safe for release."[32] This committee should also be cognizant of the processes for collecting the samples on Mars and for allocating the samples for scientific study once they are released to the Mars Curatorial Facility. **The SSE Survey endorses the concept that a single advisory structure supervise all aspects of returned Mars sample collection, containment, characterization and hazard assessment, and allocation. This advisory structure might be international in composition.**

Sample Curatorial Facilities

To prevent cross-contamination between samples from different planetary bodies, the samples must be handled in separate facilities. The Mars Curatorial Facility, for example, will be required once the martian samples are shown to be environmentally safe. Construction of such a facility is considered to be consistent with current practice and experience, for example, for lunar samples and Antarctic meteorites. Sample allocations from the Lunar Curatorial Facility and from the Antarctic Meteorite Laboratory are under the guidance of advisory committees (the Curation and Analysis Planning Team for Extraterrestrial Materials and the Meteorite Working Group). These advisory committees are the successors of the Lunar Sample Analysis Planning Team, which oversaw the preliminary examination of the returned lunar samples and lunar sample allocations. These committees best exemplify the advisory committee proposed above for the oversight and analysis planning for Mars samples.

The Need for an Early Sample-Return Program

When addressing the future of solar system exploration, it is clear that a natural process of maturation has occurred. Missions have progressed from reconnaissance flyby and orbiter missions, to detailed characterization from more sophisticated, long-lived orbiters and from landed missions with in situ investigations, to sample return from small bodies, and finally to future sample-return missions from planets, comet surfaces, and asteroids. Science questions tied to samples returned from diverse planetary environments form a prominent theme in the individual panel reports of Part One that lead to many of the specific mission recommendations for the next decade (see Chapter 8). This recurring emphasis on sample return is a direct result of the sophisticated level of scientific questions that can now be posed and answered. There is nevertheless a host of interwoven issues and requirements for each of the sample-return missions, many of which would benefit from a thorough and integrated approach.

These issues were addressed by some of the panel reports (see, for example, Chapter 2). The broad common categories that must be addressed by each mission include the following:

• Consideration of the means by which a sample is acquired and returned to Earth. Although each planetary environment is different, the technology required for implementation often applies to more than one situation. Experience gained in one environment may provide valuable benchmarks for another. Examples include these:

—Experience with end-to-end sequencing for lunar sample acquisition would provide confidence in undertaking the more complex Mars sample return;

—The architecture for returning samples from the Mars gravity-well could be comparable to that needed for a similar Venus activity; and

—Anchoring a spacecraft on and acquiring samples from a low-density, near-Earth object would provide experience needed for similar activities on a complex, multiphase comet nucleus (or vice versa).

• Requirements for the development and maintenance of Earth-based, state-of-the-art analytical capabilities to study the returned samples. Instead of developing instruments for launch into space, extremely capable and sophisticated instruments must be developed for use in Earth-based laboratories for data acquisition and the extraction of science information from the returned samples. A review of the analytical capabilities in U.S. laboratories for sample analysis has identified the need for the development of new instrumentation and for upgrading U.S. laboratories. In response, a start in this direction has been made by the new and fully competitive Sample-Return Laboratory Instrumentation and Data Analysis Program. There is a need to improve and to develop, on a continuing basis, novel, sensitive instrumentation and to develop the analytical techniques applicable to specific samples and new science questions. The development of a specific instrument normally takes 5 to 7 years. Gaining experience and developing techniques for such an instrument require an additional 2 years. While some instruments may become commercially available, it is more likely that, with adequate support, key novel instruments will be developed through the close interaction between industry and researchers.

• Need for appropriate analytical facilities along with personnel who have the expertise to use them. Diverse instrumentation is necessary for sample analyses. For major instruments, it is likely that the use will be shared by many investigators and that such instruments may reside in regional Centers of Excellence and require a facility-type operation. It is anticipated that most of these regional facilities will be associated with educational institutions and will help train multidisciplinary researchers. It is recommended that these analytical capabilities and experience working with very small samples be developed well in advance of sample return.

• Need for planetary protection and curatorial facilities to contain samples and for procedures to handle diverse samples. Such facilities for lunar samples are already in place and in use. Facilities for the Discovery missions Stardust and Genesis are under design. Appropriate facilities for diverse samples from environments with biological potential as well as from environments whose integrity must be maintained (e.g., temperature, pressure, composition) need to be implemented and sample-handling experience gained well in advance of sample return.

As we enter the detailed exploration phase of planetary exploration, sample return of the basic "ingredients" that compose the solar system will become an integral element of fundamental science return, and with it a host of new challenges need to be addressed. This will require support on a continuing basis for the preparation of and in conjunction with an exciting suite of sample-return missions. Such support can be provided through the identification of a new sample-return program comparable to Missions Operations and Data Analysis. Samples from Stardust, Genesis, and the ISAS mission MUSES-C will become available during the next 4 to 6 years. For the next decade and beyond, with the expectation of additional samples returned from the Moon, the surface of a comet, Mars, and possibly NEOs, a stable program will be required to ensure that the Earth-based component is sufficiently strong to fulfill the science objectives. **The SSE Survey recommends that NASA establish, well before samples are returned from planetary missions, a sample-return program to address analytical and facility issues and the training of researchers in an integrated manner. Such a program will allow focus on the optimization of science and technology resources.**

PUBLIC RELATIONSHIPS: OUTREACH AND EDUCATION

NASA has been engaged in education and public outreach activities since its inception in 1958. During the mid-1990s, the NASA Office of Space Science formalized an E/PO strategy that includes education communities, space scientists, and related NASA organizations.[33] The implementation of this strategy was formulated by an E/PO Task Group appointed by the Space Science Advisory Committee. A key element of the implementation is to "leverage" activities through collaborations with other organizations and institutions, such as planetaria. An integral part of OSS's E/PO goal includes training activities to help create a scientific workforce for the future. The program is well conceived to achieve these goals and on its way to becoming a hallmark for other governmental agencies.

The OSS E/PO is organized into four forums, each of which corresponds to OSS themes, including Solar System Exploration (SSE). The SSE E/PO forum, directed through the Jet Propulsion Laboratory, provides sustained efforts and continuity of educational activities beyond those of short-term missions or activities undertaken by individual researchers. Part of the OSS E/PO program is the concept of "brokers," which are regional centers with the goal of interfacing between the needs of various E/PO ventures and planetary scientists.

The OSS E/PO sponsors a wide variety of activities and collaborations, implemented through missions, research activities, formal education projects, and informal projects. For example, in the year 2000, some 614 events for educators were held across solar system exploration activities and involved more than 42,000 attendees; in addition, more than 600 public events were held, reaching more than 662,000 participants. Concurrently, 85 permanent museum exhibits were supported, and 11 traveling exhibits involving solar system exploration were developed.

Planetary missions provide an unparalleled opportunity to capture student and public attention in science, engineering, and exploration. Recognizing this high potential, all NASA flight programs are required to devote 1 to 2 percent of their total budget to E/PO. Typically, each flight project develops its own set of activities. The E/PO components developed through principal-investigator-led flight projects, such as Discovery missions, have been particularly effective. In these projects, E/PO is typically "leveraged" through other organizations (including non-NASA groups), identified and cultivated by the principal-investigator team. All recent planetary missions, including Galileo, Cassini, Deep Impact, Messenger, Contour, Stardust, and various Mars missions, have extensive E/PO activities.

Current NASA Research Announcements for OSS programs provide the opportunity for planetary scientists accepted for funding to submit proposals for E/PO activities as supplements to their research projects. The selection of these supplemental awards is based on the recommendations from reviews established separate from the science research review panels, but which include educators and scientists.

The formal education aspect of the SSE E/PO includes teacher preparation, student support, and funding of the National Education Standards. For teacher preparation, the SSE goal is to train 7,500 teachers annually, with the potential to reach 225,000 students. Student support is provided through programs such as Radio JOVE, which teaches the scientific method to students in grades 6 through 14 using radio astronomy to observe the Sun or Jupiter. National Education Standards have been derived for the United States.[34] To support the implementation of the standards, the SSE E/PO has developed a pilot program that demonstrates how results from solar system exploration can be used to meet specific curriculum requirements.

There is widespread agreement that a significant strength of the SSE E/PO program is the direct involvement of principal investigators with students, teachers, and the public. Particularly valuable are partnerships with organizations (e.g., the Planetary Society) and industry during missions. The opportunity to interact with active scientists and to ask questions is greatly appreciated by these audiences. Participation by students and teachers in projects, active missions, and scientific meetings is considered excellent first-hand learning experience. Similarly, secondary-school class participation in active research through the collection of data and interaction with scientists has been highly successful. However, these activities typically involve small numbers of people and substantial commitment by planetary scientists. Consequently, activities with a multiplier effect are considered to be more cost-effective. For example, activities such as NASA's Solar System Ambassadors program, in which individuals are identified within regions to serve as local contacts, have worked well. In addition, more of the results of solar system exploration should be incorporated into undergraduate and graduate curricula. This could be achieved by working closely with authors and publishers of textbooks, including offering help at the review stages of publication.

One significant issue associated with the various science principal investigator (PI)-led E/PO efforts is the general lack of recognition by institutions and peers for E/PO activities. Considerations of promotion and tenure place little weight on such activities, and E/PO publications are seldom considered to be significant in the PI's publication record. Consequently, most PIs conduct E/PO on the side, because they feel it is important, but understand that their efforts are unlikely to be recognized or rewarded.

Most of the current SSE E/PO principal-investigator-led activities appear to be focused on teachers and students, with relatively little attention given to the general public. Some planetary scientists noted that research-linked E/PO proposals for activities focusing on the adult population tend to be rejected within the current SSE E/PO framework. Although it is recognized that the OSS E/PO sets a priority on educating teachers and students, it is also important to educate the general population about broad science topics and more specifically, solar system exploration goals and results. Enabling interactions with active planetary scientists could be very effective for this purpose.

Nearly everyone agrees that having an E/PO program within SSE, and particularly the involvement of PIs is good. However, many planetary scientists view the SSE E/PO program as being excessively bureaucratic, especially when the broker-facilitator system is taken into account. Although many PIs consider this system to have merit in principle, they see it as ineffective in practice. Moreover, it is not clear how the lines of responsibility are drawn between NASA's Public Information and Education and Public Outreach offices or how the various activities are coordinated.

The requirement of incorporating E/PO for specific projects, such as Discovery missions, is considered meritorious, and most planetary scientists agree that the current funding levels of 1 to 2 percent are about right within the SSE program. In most implementations, planetary scientists and education specialists work hand-in-hand to derive innovative and effective activities for communicating solar system exploration to students, teachers, and the public. In many respects, these programs serve as models for SSE E/PO in general. E/PO activities proposed as part of the overall research program, however, have not worked very well, primarily because of the review process and the lack of sufficient funds. For example, many PIs put substantial effort into preparing "add-on" E/PO activities as part of their research grants only to learn later that very few of the E/PO activities were funded. Moreover, in many cases they received little or no feedback on their E/PO proposals.

In summary, the SSE E/PO program is considered to have a solid foundation and to be well organized and managed. An appreciable strength is the close linkage to active planetary scientists and flight projects, and the partnering with other programs, both within NASA and outside the space science program. Areas for improvement include better communication with the planetary science community, strengthening the review process for various elements of the E/PO program, and improving the linkages to nonflight research projects.

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7

Priority Questions for Solar System Exploration, 2003-2013: The Basis for an Integrated Exploration Strategy

The 15 themes and more than 100 scientific questions spanning six categories of targets listed in Part One give a clear view of the scope, complexity, and diversity of contemporary solar system studies. They provide evidence for the richness and breadth of the knowledge that has been gained from four decades of solar system exploration. These questions also tell of how much more there is to learn with regard to vital fundamental issues about the solar system. To address these questions, the SSE Survey's panels proposed a broad range of future flight-mission candidates (see Part One), which are summarized in Table 7.1. The purpose of this chapter is to integrate the many scientific questions posed by the individual panels into a small set of key questions of the highest scientific priority, from which it is possible to derive a practical program of exploration for the next decade and a glimpse of the future that it heralds.

SETTING PRIORITIES

Rational judgments as to scientific priorities must take into account contemporary motivations for solar system exploration, which tend to be reflections of the most profound questions and the most significant of recent discoveries. The most basic motivating questions for solar system exploration, which also reflect the interests of the public, must play a role in setting priorities for the future: Are we alone? Where did we come from? What is our destiny? The discussion in the previous chapter documents the intimate associations of these questions with a robust planetary exploration program.

Assessment of priorities for the next decade must take into account the discoveries and successes of the recent past and the potential for resolution of high-level questions. In its analysis of the inputs from its panels and from the solar system exploration community (see Appendix B) the SSE Survey arrived at a list of what it asserts to be the most significant discoveries of the past decade (see Box 6.1). Moreover, the many questions raised in Part One illustrate some of the more profound mysteries that still confront us (see Box 6.2). Lastly, the Survey notes that it is intrinsic to the nature of science that priorities must be continually adjusted to take account of new findings, and that such adjustments are sometimes unexpected and sudden.

TABLE 7.1 Mission Concepts Proposed by the SSE Survey's Panels

Panel	Mission Concept Name	Cost Class
Inner Planets	**Venus In Situ Explorer**	Medium
	South Pole-Aitken Basin Sample Return	Medium
	Geophysical Network Science	Medium
	Venus Sample Return	Large
	Mercury Sample Return	Large
	Discovery missions	Small
Primitive Bodies	**Kuiper Belt-Pluto Explorer**	Medium
	Comet Surface Sample Return	Medium
	Trojan/Centaur Reconnaissance Flyby	Medium
	Asteroid Rover/Sample Return	Medium
	Comet Cryogenic Sample Return	Large
	Discovery missions	Small
Giant Planets	**Cassini Extended**	Small
	Jupiter Polar Orbiter with Probes	Medium
	Neptune Orbiter with Probes	Large
	Saturn Ring Observer	Large
	Uranus Orbiter with Probes	Large
	Discovery missions	Small
Large Satellites	**Europa Geophysical Explorer**	Large
	Europa Lander	Large
	Titan Explorer	Large
	Neptune Orbiter/Triton Explorer	Large
	Io Observer	Medium
	Ganymede Orbiter	Medium
	Discovery missions	Small
Mars	**Mars Sample Return**	Large
	Mars Science Laboratory	Medium
	Mar Long-Lived Lander Network	Medium
	Mars Upper Atmosphere Orbiter	Small
	Mars Scout missions	Small

NOTE: Missions in boldface are a short list developed in this chapter in response to the 12 key scientific questions.

Judging scientific priority requires careful consideration and choice of the criteria that are used to make the judgment. The SSE Survey's criteria are these:

- Scientific merit,
- "Opportunity," and
- Technological readiness.

The scientific merit of a question is measured by asking the following questions (listed in order of importance):

1. Does the question's answer have the possibility of creating or changing a paradigm?
2. Might the new knowledge have a pivotal effect on the direction of future research?
3. Will the knowledge gained substantially strengthen the factual base of our understanding?

"Opportunity" has to do with the practical matter of achieving a resolution to the question under consideration. A positive measure of opportunity could be a favorable budgetary situation, or the favorable orbital configuration of a planet. Other possibilities exist—for example, successes in related research in another scientific field, or the concurrent development of a mission or a technology with related objectives.

Assessment of technological readiness is a powerful tool for making judgments, as is seen more clearly in the following chapter on mission priorities. It can also be of use in judging the relative priorities of fundamental scientific questions. For example, if answering such a question demands deep drilling into the subsurface of some distant solar system body and the subsequent return of a sample to laboratories on Earth, this will surely affect that question's priority with respect to a question that perhaps has equal scientific merit but requires little more than, say, the easier task of collecting remote-sensing data for its resolution.

TWELVE KEY SCIENTIFIC QUESTIONS THAT UNDERPIN THE OVERALL EXPLORATION STRATEGY

The SSE Survey defines four broad, crosscutting themes that integrate the various goals identified by the panels in Part One:

- The First Billion Years of Solar System History;
- Volatiles and Organics: The Stuff of Life;
- The Origin and Evolution of Habitable Worlds; and
- Processes: How Planetary Systems Work.

Next, the SSE Survey identifies 12 top-level questions that represent the distillation of more than 100 individual questions identified by the Survey panels; the 12 questions are categorized within the four crosscutting themes.

- *The First Billion Years of Solar System History.* The processes that occurred during this epoch propelled the evolution of Earth and the other planets. Planetary-scale dramas were played out during those formative years, including the emergence of life on Earth. Yet this epoch in the solar system's history is poorly known. Three top-level questions emerge:

1. What processes marked the initial stages of planet and satellite formation?
2. How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas giant sibling, Saturn?
3. How did the impactor flux decay during the solar system's youth, and in what way(s) did this decline influence the timing of life's emergence on Earth?

- *Volatiles and Organics: The Stuff of Life.* We are truly made of star-stuff. Life requires organic materials and volatiles, notably liquid water, originally condensed from or acquired by the protoplanetary nebula and later delivered in some degree to the planets by organic-rich cometary and asteroidal debris. The distribution and transport of volatiles and organics are intimately linked to the evolution of our planetary system and the state in which we find it today. These three top-level questions emerge:

4. What is the history of volatile compounds, especially water, across the solar system?
5. What is the nature and history of organic material in the solar system?
6. What global mechanisms affect the evolution of volatiles on planetary bodies?

- *The Origin and Evolution of Habitable Worlds.* Our concept of the "habitable zone" is being expanded by recent discoveries on Earth and elsewhere in the solar system. Whether or not life has taken hold in the solar system beyond Earth, the implications are equally profound. Understanding our planetary neighborhood will help to trace the evolutionary paths of the other planets, and the fate of our own. The four top-level questions that emerge are these:

7. Where are the habitable zones for life in the solar system, and what are the planetary processes responsible for producing and sustaining habitable worlds?
8. Does (or did) life exist beyond Earth?
9. Why did the terrestrial planets differ so dramatically in their evolution?
10. What hazards do solar system objects present to Earth's biosphere?

- *Processes: How Planetary Systems Work.* Understanding the operation of fundamental processes is the firm foundation of planetary science. Studies of planetary interiors, surfaces, atmospheres, rings, and magnetospheres are windows into the evolution of worlds. Studying processes in our planetary system allows extrapolation to extrasolar planets, and of those planetary systems to ours. Two top-level questions emerge:

11. How do the processes that shape the contemporary character of planetary bodies operate and interact?
12. What does the solar system tell us about the development and evolution of extrasolar planetary systems and vice versa?

All of these questions are of high scientific merit. Most have the potential to lead to major paradigm shifts in our general understanding. All have the potential of being pivotal and could lead to new pathways in solar system research. All will lead to an increase in the factual base of our knowledge. All, as indicated below, can be substantially addressed with reasonable levels of technical development, and most can be addressed within the envelope of opportunities that are implied in the proposed New Frontiers program and NASA's ongoing Mars and Discovery flight programs, along with less frequent Flagship-class missions. Many of these questions build directly on recent discoveries. They will also help elucidate the outstanding mysteries about the nature of the solar system and make significant progress toward answering the most basic motivating questions. The missions with the greatest potential for answering these high-priority questions are specified below and listed in Table 7.2.

RECOMMENDED MISSIONS TO ANSWER KEY QUESTIONS

The First Billion Years of Solar System History

What Processes Marked the Initial Stages of Planet and Satellite Formation?

The planetary system accreted from a spinning disk of gas and dust (the solar nebula) surrounding the proto-Sun about 4.6 billion years ago. Beyond Neptune, the solid material never accreted into the major planets but remains as a vast collection of objects known as the Kuiper Belt. These icy bodies hold clues not only to the origin of the outer planets but also to the origin of Earth's inventory of volatiles and possibly to the origin of prebiological organic material on Earth. Because of the cold temperatures at trans-neptunian distances and because smaller objects are less likely to have undergone internal differentiation, the smaller Kuiper Belt objects (KBOs) are thought to be relatively unmodified since their formation. It is therefore expected that studies of the chemical composition of KBOs will provide knowledge of the pathways of volatile and organic molecular materials from their interstellar origins to their disposition in Earth's hydrosphere, atmosphere, and biosphere. The Kuiper Belt-Pluto Explorer (KBP) mission constrains the bulk properties of several KBOs, including the best-studied of these icy objects, Pluto and Charon, by determining their densities. Radii are precisely measured by high-resolution imaging and solar occultations, and masses by measurement of the gravitational deflection of the spacecraft. Moreover, the mission observes the surfaces and atmospheric constituents of Pluto, Charon, and other KBOs at high spatial and spectral resolution in order to determine the composition and distribution of volatiles. These measurements cannot be performed with necessary precision from Earth-based telescopes but can be achieved with KBP. Thus, the KBP mission is central to addressing the nature and composition of the planetesimals that are

TABLE 7.2 Most Relevant Missions to Address Fundamental Scientific Questions

Fundamental Scientific Question	Most Relevant Missions[a]
The First Billion Years of Solar System History	
1. What processes marked the initial stages of planet and satellite formation?	Comet Surface Sample Return Kuiper Belt-Pluto Explorer South Pole-Aitken Basin Sample Return
2. How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas-giant sibling, Saturn?	Jupiter Polar Orbiter with Probes Neptune Orbiter with Probes
3. How did the impactor flux decay during the solar system's youth, and in what way(s) did this decline influence the timing of life's emergence on Earth?	Kuiper Belt-Pluto Explorer South Pole-Aitken Basin Sample Return
Volatiles and Organics: The Stuff of Life	
4. What is the history of volatile compounds, especially water, across the solar system?	Comet Surface Sample Return Jupiter Polar Orbiter with Probes Kuiper Belt-Pluto Explorer
5. What is the nature of the organic material in the solar system? Its history?	Cassini Extended Comet Surface Sample Return Titan Explorer
6. What global mechanisms affect the evolution of volatiles on planetary bodies?	Mars Exploration Program Mars Upper Atmosphere Orbiter Venus In Situ Explorer
The Origin and Evolution of Habitable Worlds	
7. Where are the habitable zones for life in the solar system, and what are the planetary processes responsible for producing and sustaining habitable worlds?	Europa Geophysical Explorer Mars Long-Lived Lander Network Mars Sample Return Mars Science Laboratory
8. Does (or did) life exist beyond Earth?	Europa Lander Mars Sample Return
9. Why did the terrestrial planets differ so dramatically in their evolution?	Mars Long-Lived Lander Network Mars Sample Return Mars Science Laboratory Venus In Situ Explorer
10. What hazards do solar system objects present to Earth's biosphere?	Large Synoptic Survey Telescope
Processes: How Planetary Systems Work	
11. How do the processes that shape the contemporary character of planetary bodies operate and interact?	Cassini Extended, Comet Surface Sample Return, Europa Geophysical Explorer, Jupiter Polar Orbiter with Probes, Kuiper Belt-Pluto Explorer, Mars Long-Lived Lander, Mars Sample Return, Mars Science Laboratory, Mars Upper Atmosphere Orbiter, South Pole-Aitken Basin Sample Return, Venus In Situ Explorer
12. What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?	Cassini Extended Jupiter Polar Orbiter with Probes Kuiper Belt-Pluto Explorer Large Synoptic Survey Telescope Neptune Orbiter with Probes

[a]This column lists alphabetically only what the SSE Survey considers to be the *most* relevant mission candidates to address the scientific question. However, the Survey recognizes that some of the mission candidates could address specific aspects of a scientific question even if not listed. Missions within the Discovery program could fall in any of the cells in this column.

best preserved from the initial stages of planet and satellite formation. The value of this mission increases as it observes more KBOs and investigates the diversity of their properties. KBP will make the first survey of this most poorly known but very significant portion of the solar system.

The Kuiper Belt is the birthplace of short-period comets; therefore, sampling one of these comets is a means of examining the material from which the planets were built. The Comet Surface Sample Return (CSSR) mission will gently collect material from one or more sites on the surface or in the near-surface layer of a short-period comet and return it to Earth. This will permit a full suite of sophisticated elemental, isotopic, organic, and mineralogical measurements to be performed in terrestrial laboratories, studies that will yield unprecedented information on the materials and chemical processes that dominated the initial stages of planet and satellite formation. Although it is ultimately desirable to return a nucleus sample at a temperature sufficiently low to preserve the full suite of ices, the highest priority is given to a mission returning the full suite of organic materials and non-ice minerals from the surface of an accessible short-period comet.

The Moon records some of the most ancient history of terrestrial planet evolution. The Apollo and Luna missions investigated a limited region of the Moon's nearside and did not resolve fundamental questions of how the Moon's interior differentiated into layers after its formation. The recently recognized South Pole-Aitken Basin is the largest known impact structure in the solar system and the oldest and deepest well-preserved impact structure on the Moon. This giant basin allows access to materials from the interior of the Moon. The South Pole-Aitken Basin Sample-Return (SPA-SR) mission will obtain samples of materials produced during this enormous impact event and return them to Earth. Analyses of these samples in terrestrial laboratories will permit detailed characterization of the mineralogy, elemental composition, and isotopic makeup of the lower crust and upper mantle of the Moon. This will allow the several models for early lunar evolution to be tested and distinguished, providing insight into processes that are likely to have occurred on Earth and the other terrestrial planets during the initial stages of their formation.

Over What Period Did Jupiter Form, and How Did Its Birth Differ from That of the Ice Giants?

During the formation of the giant planets, timing is critical, with dramatically different consequences for the inner solar system depending on whether giant planet formation was slow or fast. A commonly cited model is that the gas giant Jupiter formed relatively slowly, in about 10 million to 100 million years, by condensation of gas around an accumulated rock-ice core of about 10 Earth masses. If this occurred, then Jupiter's composition should reflect that of an evolving solar nebula while the solar wind was blowing the nebula away, rather than a pristine nebula. Beyond Jupiter, where the density of the solar nebula was very low, the other giant planets formed even more slowly. Consistent with this, the bulk properties of Uranus and Neptune suggest that these ice giant planets formed too late to capture the gas of the solar nebula. Without Jupiter's enormous gravitational effect to disturb them, other solar system bodies would have formed in a relatively benign environment.

On the other hand, observations of gas disks around nearby stars show that the gas is depleted on time scales of just a few million years, suggesting that the formation of the giant planets may have been relatively rapid. If Jupiter formed relatively quickly, in about 100,000 years by the process of hydrodynamic collapse, then the planet should have a negligible core. In this case the planet's composition must represent a relatively pristine sample of the solar nebula. This model is attractive because it might partly explain the apparent abundance of gas giants around other stars, which are commonly in close-in orbits where rock-ice cores seem unlikely to have formed. A quickly formed Jupiter would have prevented objects in what is now the asteroid belt from ever forming into a single planet, and inside the asteroid belt, Earth and other terrestrial planets would have been subjected to a rain of impacting objects scattered by the forming giant planet.

Whether Jupiter formed rapidly or slowly can be deduced by whether the planet has a rock-ice core. Thus, the existence of a core is key to whether Jupiter's composition reflects the pristine or evolved solar nebula and whether the planet's formation dramatically affected the burgeoning inner solar system. The Jupiter Polar Orbiter with Probes (JPOP) mission concept reveals whether Jupiter has a rock-ice core and determines its mass, by carefully measuring the planet's gravity field. Moreover, remote-sensing instruments and three deeply penetrating probes search for water and other volatiles and measure their abundances to provide compositional clues into the nature of the solar system's largest planet and the timing of its formation.

The Neptune Orbiter with Probes (NOP) mission concept samples a distinctly different class of giant planet, an ice giant. Neptune's chemistry will be measured by remote-sensing instruments and in situ with entry probes. This enables direct comparison between an ice giant (Neptune) and a gas giant (Jupiter) in terms of their chemistries, apparent time scales of formation, and effects on the evolution of the inner solar system.

How Did the Impactor Flux Decay During the Solar System's Youth, and in What Way(s) Did This Decline Influence the Timing of Life's Emergence on Earth?

The formation of the massive gas and ice giant planets probably had a profound influence on the early cratering rate throughout the solar system as they cleared their formation zones of unused debris. A sustained, solar system-wide rain of projectiles could have resulted, and this may have delayed life from gaining a foothold on planet Earth.

The lunar impact record, dated by collected rock samples, is used to extrapolate surface ages throughout the solar system. However, there is considerable uncertainty in the early flux of impacts, with two models proposed. In one, the flux decayed exponentially with time. In the other, the flux peaked at about 4 billion years in a period of enhanced bombardment that would have profoundly influenced all of the terrestrial planets. These two scenarios have vastly different implications for the conditions under which life might have emerged on early Earth.

The record of most early events on Earth is long gone, but important information is preserved in the face of our neighboring Moon. To understand the conditions on early Earth, it is important to establish the age of the Moon's oldest surface units. Dating of samples returned from the interior of the recently identified South Pole-Aitken Basin, a major impact structure on the Moon's farside, would establish a benchmark date for this earliest chronology. From this benchmark, the ancient impactor flux would be more firmly established, with important implications for early impact processes reassessed for Earth and the other terrestrial planets. The SPA-SR mission collects samples of the Moon's oldest well-preserved impact basin and returns them to Earth, where precise age-dating techniques can be applied. From the derived age of the South Pole-Aitken Basin impact event, a vital point of reference is established for the cratering rate during the earliest history of the Moon and infant Earth. This is a well-grounded and straightforward experiment that builds on a substantial base of knowledge about our satellite, consolidating its position as a cornerstone for understanding the history of Earth and the other terrestrial planets.

If a solar system-wide rain of projectiles did indeed arise from the formation of the giant planets—notably Uranus and Neptune—then the formation of the latter may also have dynamically excited the Kuiper Belt, leading to its present, collisionally sculpted structure and triggering an influx of KBOs into the inner solar system. An investigation of Pluto, Charon, and Kuiper Belt objects will yield a valuable record of the size distribution and flux of impactors within this yet-unexplored region. The atmospheric escape rate on Pluto and inferred kilometers' worth of volatile sublimation erosion of its surface over the age of the solar system suggest that Pluto's surface may be young and hence may record the present-day impactor rate and impactor size distribution in the Kuiper Belt. In contrast, the record on Charon and other KBOs is expected to be cumulative and to reflect the size distribution and flux of impactors in the ancient Kuiper Belt before clearing occurred. The comparison of Pluto to Charon and other KBOs thus has important implications for whether the late heavy bombardment was a solar system-wide phenomenon, indeed whether or not it occurred at all.

The KBP mission will image the sunlit hemispheres of Pluto and Charon at resolutions sufficient to determine the populations of large craters on their surfaces and to lead to an understanding of the modifying geological processes that have affected each surface. Analysis of these images will constrain the role that the clearing of the Kuiper Belt played in the bombardment of the inner solar system and in the transport of volatiles and organics from the deep outer solar system to early Earth.

Volatiles and Organics: The Stuff of Life

What Is the History of Volatile Material, Especially Water, Across the Solar System?

Earth formed too hot to contain the large proportions of volatile materials now present, giving rise to the idea that its volatiles, including water, were delivered to the terrestrial planets after their accretion. Even Jupiter may have received much of its complement of volatiles from farther out in the solar system. The observed comets are volatile-rich, and many move in orbits that cross those of the planets, resulting in collisions. Comets are leading candidates as deliverers of volatiles to the planets, including an uncertain fraction of the water now found in Earth's oceans. Asteroids from the outer regions of the main belt may also contain volatiles in sufficient abundance to contribute significantly to the terrestrial planets. For these reasons, strong scientific motivation exists for exploring the reservoirs and transport mechanisms of volatiles in the solar system.

The CSSR mission will approach the surface of a short-period comet and gently collect material from one or more sites on the surface or in the near-surface layer, returning organics and non-ice minerals together with water maintained in a frozen state. While this mission does not address the full range of scientific issues that could be accomplished by collection of volatile-rich material from depth and returned at deep cryogenic temperatures, laboratory analyses of the cometary volatile minerals will firmly establish the chemical standard for the elemental and isotopic abundances in short-period comets. Such comets are thought to come from the Kuiper Belt, which contains some of the most primitive, unprocessed material in the solar system. Although repeated trips through the inner solar system will have altered the surface regions of a comet considerably, many important chemical ratios will be preserved, providing important insights into the history and transport mechanisms of water and other volatiles in the solar system.

The Galileo probe returned data within Jupiter where the pressure reached some 22 bars, but it entered the gas giant planet in an unusually dry downdraft region and so did not sample the deep-water abundance that is believed to be characteristic of the planet as a whole. As a consequence, the water abundance in Jupiter remains uncertain by at least an order of magnitude. The JPOP mission sends three probes deep into Jupiter's clouds at different latitudes to measure the abundances of jovian water and other elements. In addition to determining composition with depth, the probes also measure winds, temperatures, clouds, and sunlight to a depth where the pressure reaches 100 bars. Understanding the abundance of jovian water is very important to understanding the volatile history of Earth and other planets, because ice is the medium by which other, less-abundant volatiles would have been incorporated into Jupiter by planetesimals, and, similarly, could have been transported to the inner solar system, including Earth.

What Is the Nature of the Organic Material in the Solar System, and What Is Its History?

Stardust, a Discovery mission to return minute samples of cometary dust, is under way and will provide information about the chemical composition of dust grains captured during flight through the coma of an active comet at high velocity. More comprehensive investigations demand access to a larger sample of cometary matter, preferably one collected directly and gently from the nucleus in order to preserve the composition and structure of the sample. The CSSR mission will collect a full suite of cometary organic materials and non-ice minerals, and return them to Earth, where detailed elemental, isotopic, organic, and mineralogical measurements can be performed. The mission provides a vital stepping-stone by sampling the organic and nonvolatile mineralogy of a comet. It would provide fundamental new data about the chemical and structural properties of prebiotic organic matter, addressing vital questions such as these:

- What is the handedness of cometary molecules, and what bearing does this have on the handedness of life on Earth?
- What is the ratio of carbon chain molecules to carbon rings in the comets, and how does this compare with the corresponding quantities in the interstellar dust?

- Were the materials in comets incorporated at low temperatures with little modification, as suggested by the abundance of the volatiles carbon monoxide and carbon dioxide? Or was the constituent material first cycled through a wide range of solar distances and temperatures by turbulent motions in a heavily mixed solar nebula, as suggested by the presence of high-temperature silicates in comets?

The atmosphere and surface of Titan are inferred to be rich in organic materials, providing a natural arena for the study of organic chemistry over temporal and spatial scales unattainable in terrestrial laboratories. Understanding the pathways of organic synthesis on Titan may hold answers to the evolution of prebiotic chemistry on ancient Earth. Cassini will enter orbit around Saturn in July 2004 and will release the Huygens probe into Titan's atmosphere in 2005. Huygens will sample Titan's atmosphere in situ, identifying and quantifying its constituents. Huygens descent data and mapping by several orbiter instruments will provide a first close look at Titan's haze-shrouded surface and identify possible regions of liquid hydrocarbon lakes or seas. Results from Cassini and Huygens will elucidate the satellite's surface state, atmospheric composition, and complex chemical processes. However, after the nominal Cassini mission ends, coverage of Titan's surface will be incomplete. Cassini Extended (CasX) provides an opportunity to follow up on major discoveries of the nominal Cassini-Huygens mission with focused orbiter remote-sensing observations and scientific analyses.

Because the pathways and products of long-term organic evolution on Titan may have implications for the origin of life on Earth, it is important to thoroughly investigate the natural organic chemistry in the atmosphere and on the surface of Titan. A future Titan Explorer (TEX) mission might consist of an orbiter and an "aerobot" that is able to move within the atmosphere to obtain samples and conduct experiments at multiple locations. The craft would include aerosol collectors, mass spectrometers, and other atmospheric-structure and -composition instrumentation. In addition, the system would make high-resolution remote observations of the surface from various altitudes and would descend to the surface multiple times to make close-range and possibly in situ measurements of surface composition and properties. Through analyses of the products of organic synthesis on Titan, we will better understand the prebiotic processes that led to the origin of life on Earth.

What Global Mechanisms Affect the Evolution of Volatiles on Planetary Bodies?

Once delivered to the planets, volatiles may be sequestered in surface and interior reservoirs, partitioned into the atmosphere, or lost to space. For example, on Earth, CO_2 dissolves in ocean water, precipitates as carbonate rock, and reemerges in subduction zone volcanic eruptions. On Venus, the lack of liquid water and plate tectonics precludes this mechanism, and CO_2 remains in a gaseous state and contributes to the atmospheric greenhouse. Both the CO_2 and the nitrogen abundance are similar on Earth and Venus, so a real mystery is what happened to the water that should once have been present on Venus?

The atmosphere and surface of Venus preserves records of that planet's evolutionary history, including the interaction of the atmosphere and surface rocks. Therefore, compositional and isotopic measurements of the atmosphere and of the surface rocks would reveal the planet's internal and atmospheric evolution. The proposed Venus In Situ Explorer (VISE) mission would measure the composition and isotope ratios of the atmosphere on descent and of surface rocks on landing. Moreover, the mission would retrieve a core sample and then undertake sophisticated geochemical and mineralogical measurements from a more benign environment at high altitude. These VISE results would constrain the original complement of water and other volatiles on Venus, mechanisms of volatile origin and loss, and the internal evolution of the planet. The mission is central to understanding terrestrial planet volatile evolution, which can proceed toward either supporting life or preventing its inception.

At the other extreme, Mars volatiles are largely trapped in the polar caps and in vast buried reservoirs of frozen permafrost probably overlying liquid groundwater. Mars missions currently under way, including Mars Odyssey, are revealing the past and present reservoirs of water on Mars, as well as the processes that control the distribution. Mars Exploration Program (MEP) missions offer important potential to continue the theme "Follow the water." Specifically, the Mars Long-Lived Lander Network (ML^3N) includes mass spectrometers that permit precise long-lived chemical and isotopic analysis to track the dynamics of Mars's ground-level atmosphere. Time variability of isotopic compositions will indicate sources, sinks, and reservoirs of volatiles, and the planet's atmospheric evolution.

The Mars Upper Atmosphere Orbiter (MAO) mission will study the upper atmosphere of the planet to determine its dynamics, hot-atom abundances and escape fluxes, ion escape, minimagnetospheres and magnetic reconnections, and the energetics of the ionosphere. These results will for the first time reveal the coupling between the lower and upper atmosphere of Mars and thus are key to understanding the evolution of atmospheric volatiles.

The Mars Science Laboratory (MSL)—an approved mission, currently scheduled for launch in 2009—will conduct detailed in situ investigations of a site that orbital data identify as a water-modified environment, providing critical ground-truth for orbital remote-sensing data and testing hypotheses for the formation and composition of water-modified environments. The types of in situ measurements possible on the MSL are directly relevant to martian volatile evolution, including atmospheric sampling, surface mineralogy, and chemical composition. The Mars Scout program also provides opportunities for missions that investigate the evolution of the planet's volatiles.

Thus the stage will be set for Mars Sample Return (MSR), in which samples from carefully chosen sites will be returned to Earth and subjected to a full array of analytical techniques, merging new understanding of the geological evolution of Mars with detailed knowledge of the chemistry, mineralogy, and chronology of the crust, the role of volatiles, and elucidation of the conditions that could potentially have led to the emergence of life on Mars.

The Origin and Evolution of Habitable Worlds

Where Are the Habitable Zones for Life in the Solar System, and What Are the Planetary Processes Responsible for Producing and Sustaining Habitable Worlds?

The boundary conditions for habitable zones in the solar system are principally constrained by the occurrence of liquid water and a source of energy for biological activity. On Earth, life exists wherever water occurs. Microbes thrive in both extremely hot and subfreezing temperatures, under acidic or alkaline conditions, and in the presence of high concentrations of salts or heavy metals. Life forms capable of surviving similar conditions may have existed, and might persist today, in the subsurface of Mars and within large icy satellites, notably Europa. Study and comparison of planets and satellites that have a water history allow an understanding of how habitable worlds evolve.

Mars is at the outer edge of the traditionally defined habitability zone, and today its near-surface water resides largely as ice. MEP missions will improve our understanding of the Red Planet's potential current and past habitability by investigating the distribution and history of its volatiles (see above), and through remote-sensing and in situ investigations of the geological and geochemical processes that have operated there. Debate will continue as to whether Mars supports or ever supported life—at least until samples are returned from carefully chosen sites on the planet.

The MSR missions will collect samples from carefully selected locations and return them to Earth, where they can be subjected to detailed mineralogical, chemical, and isotopic analyses. When correlated with remote-sensing and in situ data and inferred geological processes, the results of sample analyses will clarify whether the planet's environmental conditions have ever been conducive to life. Thus, MSR missions are ultimately critical to understanding the limits of habitability in the solar system.

The putative sub-ice ocean of Europa might provide a different type of habitable world, one that does not rely upon solar energy. Tidal heating provides a source of energy to maintain liquid water beneath Europa's icy carapace. Morphological features there suggest surface motions broadly analogous to the jostling of floating ice plates in Earth's polar oceans. Geological processes would allow for communication between the ocean and surface, and therefore the transport of nutrients and perhaps organisms between the surface and the subsurface ocean. Inferences about oceans within Europa and the other icy Galilean satellites have received dramatic support from induced magnetic-field measurements from Galileo, and the existence of subsurface liquid water is now widely accepted. However, many uncertainties remain regarding the level of current activity, the nature of the satellite's geological processes, the thickness of the ice shell, the chemistry of the surface and ocean, and potential energy sources for life.

The Europa Geophysical Explorer (EGE) mission will address the potential habitability of Europa. This mission orbits Europa and employs geophysical methods—specifically, gravity and altimetry measurements of Europa's tidal fluctuations—to confirm the presence of an interior ocean and characterize the satellite's ice shell. Additional remote-sensing observations will examine the three-dimensional distribution of subsurface liquid water; elucidate the formation of surface features, including sites of current or recent activity; and identify and map surface composition, including compounds of astrobiological interest. EGE is the vital next step in understanding the potential habitability of Europa and the processes that might produce and sustain habitable environments within icy satellites.

Does (or Did) Life Exist Beyond Earth?

Whether life exists in the solar system beyond Earth is among the most profound questions we can ask. Even more profound is the fact that we can make substantial progress toward answering it during the next decade and the decade beyond.

Today, Mars appears hostile to life because of its thin atmosphere and harsh radiation environment; yet life may have existed in the planet's distant past or may still exist in subsurface reservoirs. The SNC meteorites are of martian origin but, because of their origin by random impact ejection, have unknown provenance and are unlikely to be typical of the surface rocks on Mars. Already it has been suggested that the SNC meteorites contain evidence for extraterrestrial life. The ambiguous and controversial nature of the evidence, however, suggests that a definitive answer to the question of whether or not Mars fossils exist must await the return of carefully retrieved samples, as proposed for the MSR missions. The MSR missions will carefully collect and return martian samples for comprehensive examination on Earth, employing sophisticated analyses that could not be done in situ at Mars. Only close analysis using the full range of analytical facilities available in a terrestrial laboratory can provide the detail and experimental confidence to address the substantial issue of past and current life on Mars.

The popular and scientific interest in Europa lies with the possibility that its subsurface ocean might constitute a habitable zone for past or present life. Following the EGE mission, if an ocean is indeed confirmed, a subsequent Europa Lander (ELAN) mission should be aimed at in situ investigation of the surface and its chemistry. Such a mission can search for and characterize near-surface organic materials and perform detailed geophysical investigations pertinent to the potential for Europa to harbor life. The potential for life in protected environments beneath the surfaces of otherwise inhospitable worlds is a fascinating possibility, undreamed of just a few decades ago.

Why Did the Terrestrial Planets Differ So Dramatically in Their Evolution?

The terrestrial planetary bodies share many similarities, but solar system exploration has revealed that they are also fundamentally different in many other ways. The Moon, Mercury, and Mars stabilized their crusts and lithospheres early in planetary evolution and became "one-plate" planets. In contrast, Earth evolved into a dynamic, multiplated planet that is constantly renewing itself through atmospheric erosion and recycling of the crust into the interior. Venus shows no sign of active plate tectonics and may have been catastrophically resurfaced within the last billion years. Terrestrial planet atmospheres also show major differences, with Venus and Mars being CO_2-dominated, but with orders-of-magnitude different surface pressures. On Earth, liquid water provides a substantial thermal buffer to sudden changes in the climate; nevertheless, ample evidence indicates that the climate has varied considerably with time.

Climate can be altered by changes in global volcanism, solar output, celestial mechanics, and the effects of pollutants made by humans. The interactions between these influences are so complicated that they are not fully understood. Adjacent planets Venus and Mars provide compelling examples of planets whose atmospheres have evolved along very different paths from that of Earth. The thin CO_2 atmosphere of Mars represents an extreme in which temperatures are low and a significant fraction of the "atmosphere" lies buried as ice within the regolith and upper crust. It is critical to understand whether climate change has truly occurred at Mars, and, if so, what its causes and effects are.

The MEP missions will explicitly address Mars's climate change and atmospheric evolution. To understand the planet's current sources, sinks, and reservoirs of volatiles, the ML^3N mission will determine the ground-level chemical and isotopic composition of the atmosphere, including humidity, at a network of surface stations for at least 1 martian year. To better understand the longer-term evolution of the atmosphere, the MAO determines the composition and dynamics of the middle and upper atmosphere and measures the escape rate of atmospheric molecules. The MSL is scheduled to conduct detailed in situ investigations of a site that orbital data identify as a water-modified environment, testing hypotheses for the formation and composition of water-modified regions, and providing critical ground-truth for orbital remote-sensing data sets that are used to infer past water. Mars Scout missions provide the potential for focused studies of Mars climate change and atmospheric evolution not otherwise addressed in the MEP. MSR missions will establish the role of liquid water and weathering processes by enabling detailed laboratory study of the chemical and isotopic signatures of mineral samples and weathered materials. Corresponding measurements on volatiles within returned samples may provide definitive evidence of past atmospheric and chemical conditions, allowing past climate conditions to be understood.

Understanding the causes and effects of climate change also requires in situ investigations of Venus, where surface temperatures hotter than an oven are produced by a CO_2 greenhouse. Global monitoring of Venus's atmosphere and climate, in situ elemental, mineralogical, and geochemical measurements of the surface, and detailed data on the noble gas isotopes and trace gas abundances of the atmosphere are necessary to understand Venus's climate, and potentially the fate of Earth's climate. These are goals of the VISE mission, which will also prepare the groundwork for a future Venus sample-return mission.

What Hazards Do Solar System Objects Present to Earth's Biosphere?

Cosmic impact has the potential to eliminate humankind as we know it. Therefore, it is critical for us to systematically assess the magnitude of these threats. The atmospheric, geological, and biological effects of cosmic impact have become apparent only since the early 1980s, when the likely cause of the Cretaceous-Tertiary extinction was first linked to the impact of a 10-km asteroid. Even much smaller impactors still possess enormous energies and may cause local to regional devastation. At Congress's direction, NASA has supported a ground-based program to identify the NEOs larger than 1 km in diameter. This task is about 50 percent complete, with estimates for the date of completion ranging from 2010 to 2020 and beyond. The kilometer-sized impactors would be globally devastating, but much smaller projectiles would wreak unimaginable local havoc and are much more frequent. The high-altitude explosion of an 80-m-diameter body above Tunguska, Siberia, in 1908 flattened trees over a broad area. A differently aimed impact of this scale could flatten a modern city, with deaths in the millions. Bodies larger than about 300 m in size cause ground-level explosions in the gigaton range. Such impacts would devastate whole countries. There is about a 1 percent chance that such an impact will occur in the next century.[1]

Assessment of the NEO population down to 300-m scales, as part of an organized inventory of the small bodies of the solar system, is recognized as a high priority for NASA's Solar System Exploration program. Extrapolations from existing surveys suggest that the number of NEOs larger than 300 m is on the order of 10,000 to 20,000. These bodies are too faint to have been detected by the current surveys, and almost all remain undetected. For each object, we need to determine the orbital elements with accuracy sufficient to predict the probability of terrestrial impact within the next 100 years. This time scale gives sufficiently early warning for the development of mitigation strategies, as needed, and is compatible with the intrinsic time scale for dynamical chaos among the NEOs. For those objects with a non-negligible impact probability, we also need physical observations to determine the size, which, when combined with a "typical" density yields an estimate of the kinetic energy of the projectile. These goals can be achieved with the Large Synoptic Survey Telescope (LSST). Determining the physical properties of comets and asteroids is also an important goal; it can be addressed by aspects of the Discovery program.

Processes: How Planetary Systems Work

How Do the Processes That Shape the Contemporary Character of Planetary Bodies Operate and Interact?

An understanding of planetary formation, evolution, and potential habitability is possible only with a detailed knowledge of the individual processes that shape planetary interiors, surfaces, atmospheres, rings, and magnetospheres. Physical processes define the mechanisms by which planetary interiors, surfaces, atmospheres, and magnetospheres evolve and interact. Relevant interior processes include chemical differentiation and core formation and the mechanisms of heat transfer throughout planetary history. Impact cratering, tectonism, and volcanism represent geological processes that have shaped planetary surfaces throughout history. Planetary atmospheres hold the record of the volatile evolution of the planet and interactions with surface materials, weather, and climate. The nature of the processes that are responsible for the remarkable diversity of planetary ring systems must be better understood. The nature and evolution of the magnetosphere are critical to a wide range of phenomena, from planetary interior processes (e.g., core dynamos) to loss of surface and atmospheric species with time. Together, an improved and integrated understanding of planetary processes is necessary to determine fully how planets work.

Virtually all of the missions suggested in Part One contribute to a better understanding of planetary processes, ranging from our deepening knowledge of the Saturn system (CasX), to the interior structures and gaseous and magnetospheric environments of the giant planets (JPOP and NOP), the surfaces and interiors of icy satellites (EGE, ELAN, and TEX), the surface and atmosphere of Venus (VISE), impact basin formation and the interior of the Moon (SPA-SR), the history and environment of Mars (MEP), and the host of more specific aspects addressed by Discovery missions. Collectively these results will substantially enhance our understanding of planetary processes.

What Does the Solar System Tell Us About the Development and Evolution of Extrasolar Planetary Systems and Vice Versa?

Extrasolar planets are increasingly becoming a focus of both scientific and popular attention. Many more extrasolar planets will be detected in the next decade. Some will be imaged, and their spectra will be partially resolved. To provide critical ground-truth for these exciting discoveries, NASA should pursue a parallel program of close-up exploration and analysis of our own giant planets, their ring systems, and the Kuiper Belt. The solar system provides ground-truth to the study of giant planets around other stars.

The answer to the question of whether or not Jupiter has a rock-ice core is critical to understanding how the planet formed and, by extension, how extrasolar planets form. Two formation mechanisms are believed to be possible. The first, or slow process, invokes the initial aggregation of a rock-ice core of approximately 10 Earth masses. This embryo then attracts gas, but the rate at which it does so is limited by how fast the growing object can radiate energy. The second, or fast process, invokes hydrodynamic instabilities that cause a subcondensation of the solar nebula to collapse as a result of its own self gravity. Stars form this way when the density of matter in giant molecular clouds reaches a critical value. Brown stars—failed stars, that is, substellar objects insufficiently massive to sustain nuclear reactions in their cores—also form in this manner.

The rate and means of formation of Jupiter can be understood by determining whether it has a rock-ice core. Measuring the mass of Jupiter's core is a major objective of the JPOP mission. The NOP mission samples the chemistry of ice giant Neptune, enabling direct comparison to Jupiter in terms of chemistry and inferred time scale of formation. Observations of extrasolar planets—mass, radius, temperature, and composition—will be difficult to interpret unless we draw on our knowledge of giant planets in our own solar system. We need to understand how differences in bulk density translate into differences in composition and origin. The ice giants and gas giants of our solar system will help provide that knowledge.

We also need to know how atmospheric circulation and other meteorological phenomena affect the temperatures and compositions of extrasolar giant planets. These objects have clouds in their atmospheres. Clouds lead to precipitation and release of latent heat. The giant planets found close to their parent stars have large day-night temperature gradients. The temperature gradients lead to winds, which affect both temperature and composition. Clouds, precipitation, temperature gradients, and winds are meteorological phenomena. We know about these things from studying the atmospheres in our own solar system.

Determining the atmospheric composition, properties, and dynamics of Jupiter is a major objective of the JPOP mission. Three probes are deployed deep into the gas giant planet at three different latitudes, measuring composition, winds, temperatures, clouds, and sunlight, as functions of pressure to a depth of 100 bars. The NOP mission samples the chemistry and atmospheric dynamics of ice giant Neptune, enabling direct comparisons to Jupiter.

The study of protoplanetary disks can be influenced by studies of planetary rings in our own solar system. The concept of migration of bodies due to angular momentum exchange with surrounding material was first advanced in the ring context and is now a mainstay of planetary formation models. Moreover, detailed understanding of ring processes would yield significant scientific benefit to a broad range of astrophysical investigations, including studies of accretion disks, spiral disk galaxies, and the disks surrounding interacting binary stars, and investigations of active galactic nuclei. Here the Cassini mission to Saturn and the proposed NOP mission are fundamental to an understanding of ring processes and to a better understanding of the accretion of planets in the solar system and other planetary systems.

We have only just discovered the vast, unexplored region of the solar system known as the Kuiper Belt. At the same time, we have now begun to image the dust and planetesimal debris disks around other stars in our search for planets around other stars. We have discovered close analogues to our own Kuiper Belt around some of these stars—for example, around the star Epsilon Eridani. These observations show arcs and local voids that may be due to the gravitational effects of embedded large planets. If we were to look at the solar system from afar, as we look out at other planetary disks today, we would see a similar void carved by the gravitational scattering of Neptune. In order to understand and interpret imaging and spectroscopy of planetary bodies around other stars, we need to understand the structure and composition of our own Kuiper Belt. In the coming decade, studies of extrasolar planetary systems will continue from new large telescopes on the ground and in Earth orbit. At the same time, the LSST will be able to determine the distribution of objects in the Kuiper Belt in great detail, which will enable comparison with the structure of extrasolar planetary disks. Moreover, the KBP mission will explore Kuiper Belt objects, including Pluto and Charon, firsthand in order to understand their nature, composition, and evolution. These missions will provide local truth for understanding data from other stellar equivalents.

REFERENCE

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Recommended Flight Investigations and Supporting Ground-Based Activities: 2003-2013

Earlier chapters present evidence of the dramatic scope of NASA's Solar System Exploration program, evidence of the program's remarkable achievements as well as of its weaknesses, and descriptions of the remarkable breadth of the flight and Earth-based opportunities that currently exist to advance solar system science. Since it is an incontestable fact of budgetary constraints that not all these opportunities can be acted upon in the coming decade, a strategy is required that integrates the goals of the diverse elements of the program, moves to strengthen areas of weakness, and accomplishes what can be done through opportunities with both the highest scientific merit and technical readiness.

JUDGING MISSION AND RELATED PRIORITIES

The letter requesting this study called for the generation of a prioritized list of the most promising avenues for flight investigations and supporting ground-based activities. This chapter is devoted to that task. A prioritized list implies that the elements of the list have been judged and ordered with respect to a set of relevant criteria. Exactly the same criteria are used here that were used in Chapter 7 to isolate key scientific questions for the next decade: scientific merit, opportunity, and technological readiness. An assessment of *all* of these criteria together is the essential consideration in determining mission priorities. For example, it would make little sense to have as a first priority a flight mission or ground-based system that was awaiting some long-term technical development or for which no flight or budgetary opportunity existed, no matter how high the scientific merit was rated.

UNDERLYING PROGRAMMATIC REQUIREMENTS

So far, priorities have been discussed in relationship to either scientific questions or specific projects. However, programmatic requirements also need to be considered in building a truly integrated strategy. Individual flight projects recommended for the next decade rest on the base of the long-term program. The top-level programmatic priorities provide the foundation for productivity and continued excellence in planetary exploration and build on the positive aspects of the President's proposed FY 2003 budget for NASA.[1] These priorities are as follows:

1. Continue approved missions, such as the Cassini-Huygens mission to Saturn and Titan and those in the Mars Exploration Program (MEP) and the Discovery program of low-cost missions, and ensure a level of funding that is adequate both for successful operations and for the analysis of the data and publication of the results of these missions. Fundamental research programs, follow-on data-analysis programs, and technology-development programs that support these missions should also be assured adequate funding.

2. Increase the fundamental research and analysis grant programs at a rate above inflation for a decade until they are at a level consistent with the recent change in character of the Solar System Exploration program—that is, a change in the flight rate from a few large missions per decade to one or more small missions per year.

3. Establish the New Frontiers line of principal-investigator-led, competitively procured, medium-cost flight missions applicable to targets throughout the entire solar system and with a total mission cost cap at $650 million.

4. Continue the development and implementation of Flagship missions (e.g., Viking, Voyager, Galileo, Cassini-Huygens) for the comprehensive exploration of extraordinary, high-priority science targets at a rate of roughly one per decade.

5. Continue to support and upgrade the technical expertise and the infrastructure in implementing organizations that provide vital services to enable and support solar system exploration missions.

6. Continue to encourage and participate in international solar system exploration flight programs. Solar system exploration is an inherently international venture, and the U.S. program can benefit from joint ventures.

MISSION LINES AND COMPETITION

The success of the Discovery program, exemplified by the Near-Earth Asteroid Rendezvous (NEAR) mission, Lunar Prospector, and Mars Pathfinder, has convinced even the most hardened skeptic that small, relatively low-cost missions can effectively address significant scientific goals. The discipline of Discovery's competitive selection process has been particularly effective in eliminating ill-conceived concepts and has resulted in a richness of mission goals that few would have thought possible a decade ago. The planetary science community's enthusiastic support for Discovery has led to calls for the competitive acquisition of all flight projects. The experience during the past decade in developing mission concepts (i.e., various Pluto flyby and Europa orbiter mission concepts) for which traditional procedures have led to escalating cost estimates has amplified this call. The proposed line of New Frontiers missions is specifically intended to be competitively selected. Competition is seen as a vehicle to increase the scientific richness of flight missions and, perhaps of equal importance, as a device to constrain the large costs associated with flying robotic missions to the planets.

Because of the positive experience with Discovery and also because of NASA's recent success in competing an outer solar system mission in the New Frontiers cost category, **the SSE Survey strongly endorses the New Frontiers initiative. These spacecraft should be competitively procured and should have flights every 2 or 3 years, with the total cost capped at approximately twice that of a Discovery mission. Target selection should be guided by the list in this report.**

While competitive selection has its advantages, its negative aspects should also be taken into consideration, and avoided if possible. They are as follows:

- *Competition leads to secrecy in the conceptual phase of a mission.* For small missions having an adequate number of scientifically focused flight opportunities, this does not seem to be a demerit. However, with intrinsically expensive missions for which the flight opportunities may be singular and the scientific goals broad, it can be a problem. For New Frontiers missions, it does not seem advisable for conceptual scientific development to become the responsibility of a narrowly focused group in the community, no matter how well motivated they are. The selection of New Frontiers missions needs to be a continuing process involving broad community input, as has been accomplished by this decadal survey report.
- *Competition for New Frontiers missions may lead to a substantial increase in the overall costs associated with conceptual mission development during the preselection stage.* As yet, the SSE Survey knows of no estimate or clearly identified source of funds for the development of proposals for New Frontiers missions. The cost of developing a Discovery proposal to the final stage of a competition is not negligible. These costs can be expected

to increase with the size and scope of the mission. The cost to develop a New Frontiers mission proposal will be considerably more than for Discovery missions. In Discovery, these funds come partly from the overhead charged on other projects at an implementing institution and partly from NASA (particularly in the final stages of the competition). **The SSE Survey recommends an early study to determine the means for providing the funds necessary to underwrite proposal competition in New Frontiers missions.**

• *Competition may lead to conflicts of interest at NASA centers.* There are areas of unique expertise resident in single NASA centers that must be supported and maintained as necessary and required to carry out the planetary exploration enterprise (e.g., mission analysis, navigation, and deep-space communications). This expertise is often supported from institutional overhead on ongoing center missions. Since these same centers may also wish to compete, particularly for large missions, the centers will face a conflict of interest when deciding whether to make such unique services available to their competitors. **The SSE Survey recommends an early study to find ways to avoid the potentially adverse consequences of conflicts of interest relating to, for example, access to unique expertise and infrastructure at NASA centers.**

DEFINITION OF MISSION COST CLASSES

In the discussion of mission priorities that follows, The SSE Survey, at NASA's explicit request, divided missions into classes on the basis of anticipated total mission cost to completion (but without extension). The mission cost classes adopted are as follows:

- Small—less than $325 million,
- Medium—between $325 million and $650 million, and
- Large—more than $650 million.

For example, a Discovery or Mars Scout mission is a small mission by definition. New Frontier missions, as defined in the President's proposed FY 2003 budget, are equivalent to the Survey's medium-mission category. Flagship missions, for example, Europa Geophysical Explorer or Mars Sample Return, are in the large-mission category. The SSE Survey used the best information available to it in assigning cost categories to the mission concepts evaluated in this survey. Nevertheless, it must be emphasized that the cost estimates, particularly for the New Frontiers missions, are based on concept studies of limited scope. **In order to confirm the readiness of any New Frontier mission concept prior to the issuance of an Announcement of Opportunity and to certify the mission concept's qualification for this program, the SSE Survey recommends that after the first selection, an independent group conduct a certification review of the mission concept to be solicited, prior to the issuance of any Announcement of Opportunity.**

SMALL MISSIONS

The Discovery Program

The Discovery line of small missions is reserved for competed missions responsive to discoveries and is outside the context of any long-term strategy. Over the course of any 10-year period, there are certain to be new discoveries and high-science-value mission ideas that could not be discerned at the beginning of the strategic planning period. The Discovery program provides for the necessary flight program flexibility to cover these contingencies and to provide continuing new opportunities to the planetary science community for mission ideas not provided in the long-term strategic plan. The Discovery program is fundamental and invaluable for planetary exploration, but it is outside the bounds of this long-term strategic plan. Therefore, the SSE Survey makes no specific flight mission recommendations for the Discovery program, but it is compelled to make a recommendation on the value of these missions to planetary exploration**. Given Discovery's highly successful start, the SSE Survey endorses the continuation of this program, which relies on principal-investigator leadership and**

competition to obtain the greatest science return within a cost cap. A flight rate of no less than one launch every 18 months is recommended.

Flight Mission Extensions

The SSE Survey recognizes mission extensions, even multiple extensions, as significant and highly productive elements both of nominally successful missions and of missions that undergo changes of scope or time lines due to unpredictable events. The Voyager extensions to Neptune, Uranus, and the outer heliosphere are examples of the former, and the NEAR extension at Eros and the Galileo Europa/Millennium and Deep Space 1 extensions are highly productive examples of the latter. The Survey treats these extensions, which it asserts will require their own funding arrangements, as independent, small-class missions. The Discovery program can make decisions on mission extensions within the Discovery program line by trading off Announcement of Opportunity release dates. As the examples cited above indicate, the productivity and effectiveness of mission extensions in solar system exploration are unquestionable and constitute an important part of the Survey's integrated strategy. **The SSE Survey supports NASA's current Senior Review process for deciding the scientific merits of a proposed mission extension and recommends that early planning be done to provide adequate funding of mission extensions, particularly Flagship missions and missions with international partners.**

PRIORITIZED FLIGHT MISSIONS FOR THE DECADE 2003-2013

The mission concepts proposed by the SSE Survey's panels (see Part One) as future flight mission candidates are compiled in Table 7.1 in Chapter 7. They encompass missions to a diverse set of targets, from Mercury to beyond the orbit of Pluto. These concepts touch on a broad range of questions that include the formation of the solar system, the evolution of habitable worlds, the origin of life, and the fate of Earth. Some of these missions can be flown with proven technology; others require substantial technological development. It is clear that, given their cost implications, not all of the missions listed in Table 7.1 can be recommended for flight in the next decade, and therefore the SSE Survey prioritized them.

To form a scientific basis for its integrated strategy (see Chapter 7), the SSE Survey used the criteria of scientific merit, opportunity, and technological readiness to isolate 12 key scientific questions to be addressed during the next decade. It then showed how these questions relate to a small set of mission candidates, highlighted in bold type in Table 7.1, which are the mission set from which the Survey created its prioritized list of missions suitable for flight in the next 10 years.

Overall program cost constraints are a fact of life. The SSE Survey restricted the number of missions in its prioritized list to a number that it believes can be accommodated within the out-year budget profile in the President's proposed FY 2003 budget: for large-class missions, the number is limited to one, and for medium-class, the number is limited to three; these are supplemented by two extra mission candidates to account for uncertainties, to encourage further possible growth in the program, and also to give some indication of the possible direction for the program beyond the current decade. The SSE Survey's recommendations for non-Mars missions, therefore, consist of a prioritized list of five medium-class missions for the New Frontiers program, the start of one large-class mission during the decade, and one small-class non-Discovery mission extension.

Many discoveries occur in the planetary sciences over the course of a decade, and for a decadal strategy to maintain a course consistent with ongoing discoveries, the need to reconsider the priorities recommended by this Survey may arise. NASA should issue Announcements of Opportunity for New Frontiers missions that are consistent with the priorities given in this Survey. Only in the case where a new discovery changes the Survey's fundamental understanding should these priorities be reconsidered, in which case **the SSE Survey recommends that the National Research Council's Committee on Planetary and Lunar Exploration conduct a review to confirm or modify decadal survey recommendations and priorities for the New Frontiers flight program.**

The number of Discovery missions is constrained only by the funding profile. **Recognizing the Discovery program's success, the SSE Survey recommends that adequate resources be provided to sustain an average flight rate of no less than one launch every 18 months.**

While the Discovery program has resulted in great success for small missions and the New Frontiers program holds great promise for moderate-cost missions, some high-priority science investigations will require higher-cost missions. **The SSE Survey recommends that Flagship (>$650 million) missions be developed and flown at a rate of about one per decade. In addition, for large missions of such inclusive scientific breadth, a broad cross section of the community should be involved in the early planning stages.** Future survey committees should have at their disposal well-developed planning studies for missions in this class in order to make sensible decisions on prioritization. **The SSE Survey recommends that NASA conduct a series of advanced studies of Flagship mission concepts with broad community participation over each 10-year period prior to decadal surveys**. These advanced studies could be selected through a competitive process analogous to the 21st Century Mission Concepts for Astrophysics program run by NASA in the mid-1990s "to solicit innovative proposals for concept studies of new flight missions which can enhance capabilities for frontier research. . ." and "develop a menu of potential new mission concepts to be considered for the next decadal survey committee."[a]

The rationale for the SSE Survey's prioritization within the Mars Exploration Program, which places a high priority on an early Mars Sample Return mission, is treated separately below. The final prioritized list of flight-mission candidates is shown Table 8.1. As indicated, the ranking reflects the Survey's assessment of the scientific merit, technological readiness, and special opportunities associated with each mission.

Scientific Rationale for Priorities in the Medium-Class New Frontier Line

Kuiper Belt-Pluto Explorer

A mission to the Kuiper Belt, including Pluto-Charon, will provide the first exploration of this newly discovered domain in the solar system, provide important insights into the physical nature of these planetary building blocks, and allow us to survey the organic matter and volatiles that they contain. Collisions with objects such as these diverted into the inner solar system may have imported the basic volatile and molecular stock from which habitable environments were constructed in early planetary history. Little is known of the physical properties of Kuiper Belt objects (KBOs). However, what is known (several physically large objects with high rates of spin, several loosely bound binaries, and a wide range of color) indicates that they have diverse and unexpected properties. The value of this mission increases as it observes more KBOs and investigates the diversity of their properties. The SSE Survey anticipates that the information returned from this mission might lead to a new paradigm for the origin and evolution of these objects and their significance in the evolution of objects in other parts of the solar system.

Comparison of the cratering records on Pluto, Charon, and several smaller objects at a range of heliocentric distances will provide our first data on the collisional history of this region. Comparison of the surface compositions of objects in the belt with Pluto and Charon and Triton may allow us to separate evolutionary surface processes from primordial surface properties in the outer solar system. The observations, if extended to small objects, may provide information on whether comets are collisional fragments from large KBOs or are themselves primordial bodies. The surface material on KBOs may not survive entry into the inner solar system. Investigation of the composition of this material, which is probably the most primitive in the solar system, will provide an important reference for comparison with the surface materials on related bodies, including the Centaurs, the nuclei of comets, and certain near-Earth asteroids. The technical readiness of this mission is judged high, owing to the ongoing development of a technically equivalent mission concept.

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[a]Michael Kaplan, NASA Headquarters, presentation to the National Research Council's Task Group on Space Astronomy and Astrophysics, March, 1996, background materials compiled by Shobita Partnasarathy and David H. Smith.

TABLE 8.1 An Integrated Strategy for Solar System Exploration: Prioritized List of Flight Missions for the Decade 2003-2013

Mission List		Science				Technology and Opportunity	
Rank in Cost Class	Mission Concept Name	Could Create New Paradigm	Could Change Existing Paradigm	Results Will Be Pivotal	Will Add to Factual Base	Technical Readiness	Special Opportunities
SOLAR SYSTEM FLIGHT MISSIONS (non-Mars)							
Small							
1	Cassini Extended	x	xx	xxx	xxx	xxx	1
Medium							
1	Kuiper Belt-Pluto Explorer	xxx	xxx	xxx	xxx	xxx	1
2	South Pole-Aitken Basin Sample Return	xx	xx	xxx	xxx	xx	3
3	Jupiter Polar Orbiter with Probes	xx	xxx	xxx	xxx	x	
4	Venus In Situ Explorer	x	xxx	xxx	xxx	x	
5	Comet Surface Sample Return	xxx	xxx	xxx	xxx		
Large							
1	Europa Geophysical Explorer	xxx	xxx	xxx	xxx	xx	
MARS FLIGHT MISSIONS (beyond 2005)							
Small							
1	Mars Scout line	x	xx	xxx	xxx	xxx	1
2	Mars Upper Atmosphere Orbiter	x	xx	xxx	xxx	xx	2
Medium							
1	Mars Science Laboratory	x	xx	xxx	xxx	x	1
2	Mars Long-Lived Lander Network	xx	xxx	xxx	xxx	x	2
Large							
1	Mars Sample Return	xxx	xxx	xxx	xxx		2
DISCOVERY FLIGHT MISSIONS							
One launch every 18 months							

NOTE: Science and technology evaluation codes: xxx, high; xx, medium; x, modest.
Opportunity codes: 1, approved mission, operating spacecraft or celestial mechanics; 2, international; 3, technology opportunity.

Lunar South Pole-Aitken Basin Sample Return

The goal of the South Pole-Aitken Basin Sample Return (SPA-SR) mission is to understand the nature of the Moon's upper mantle and to tie down early impact chronology by returning samples from the South Pole-Aitken Basin. This basin is the largest known in the solar system and is stratigraphically the oldest and deepest impact structure preserved on the Moon. This giant excavation penetrates the lunar crust and allows access to materials from the upper mantle, and so may have a substantial effect on our current paradigm for the differentiation process. Absolute dating of returned samples, which will include both soil and diverse rock chips, could also change our understanding of the timing and intensity of the late heavy bombardment suffered by both the early Earth and Moon. The emergence of life on Earth that was ancestral to our contemporary biosphere could not have occurred until after the last global, total sterilization impact event, which likely corresponds to the end of the period of heavy bombardment.

A sample-return mission such as SPA-SR—that is, one of moderate technical difficulty—is an opportunity to gain relevant experience for much more complex sample-return missions from Mars and from Venus.

Jupiter Polar Orbiter with Probes

There are five primary objectives for the Jupiter Polar Orbiter with Probes (JPOP) mission. First, it will determine if Jupiter has a core, a question that is key to giant planet formation. One theory holds that a rock-ice "seed" of some 10 Earth masses is necessary to attract the lighter gases hydrogen and helium. Another theory says that Jupiter-sized objects can form as stars do, attracting gas, ice, and dust directly from the nebula.

Second, JPOP will measure the water abundance (hence, the O/H ratio), which is uncertain by an order of magnitude even though oxygen is expected to be the third-most-abundant element after hydrogen and helium. Water plays an important role in giant planet formation. The O/H ratio tells us how giant planets got their volatiles (H_2O, CH_4, NH_3, and H_2S) and, in particular, the extent to which the volatiles were carried from beyond Neptune's orbit to the inner solar system on icy planetesimals.

Third, JPOP will measure the deep winds to 100 bars and will give some information about the winds to thousands of bars. The deep winds may be key to the extreme stability of the weather systems observed at cloud top.

Fourth, by virtue of its cloud-skimming orbit, JPOP will measure the higher harmonics of the magnetic field, which is key to understanding how Jupiter's dynamo works.

Fifth, JPOP will repeatedly visit the hitherto unexplored polar magnetosphere, where the currents that maintain corotation (of the plasma with the planet) pass into the atmosphere and cause the jovian aurorae.

Venus In Situ Explorer

The Venus In Situ Explorer (VISE) mission is a detailed exploration and study of the composition of Venus's atmosphere and surface materials. Venus and Earth may have had very similar surface conditions early in their histories, but Venus's subsequent evolution was different from Earth's, developing an environment unsuitable for life. However, Venus is still a dynamic world with active geochemical cycles and nonequilibrium environments in the clouds and near surface that are not understood. VISE will make compositional and isotopic measurements of the atmosphere on descent and of the surface on landing. A core sample is obtained at the surface and lofted to altitude where further geochemical and mineralogical analyses are made. In situ measurements of winds and radiometry are obtained during descent and at the balloon station. Scientific data obtained by this mission would help to constrain the history and stability of the Venus greenhouse and the recent geologic history, including resurfacing. The technology development achieved for this mission will pave the way for a potentially paradigm-altering sample-return mission in the following decade.

Comet Surface Sample Return

A first sample from the near-surface layer of a comet, if taken from an active area (perhaps at sunrise when activity is low) will provide the first direct evidence on how cometary activity is driven (whether the water is very close to the surface). The Comet Surface Sample Return (CSSR) mission would provide the first real data on how small bodies accrete (physical structure at scales from microscopic to centimeters), chemical resolution of the organics in the wealth of large-mass molecules and fragments seen at Halley, and the first direct data on the selection effects that operate between the nucleus and the relatively well-studied material in cometary comae.

CSSR will also provide invaluable information on how the particles on a cometary nucleus are bound together: Is there an organic glue? Is there contact welding? It will also provide the first direct information on the scales of physical and compositional heterogeneity: Is it microscopic as seen in meteorites, or is cometary material homogeneous at the microscopic scale? Finally, CSSR will provide the first information on the macroscopic mineralogical and crystalline structure and isotopic ratios in cometary solids and also the first information on the physical relationships between volatiles, ice, refractory material, and its porosity.

Scientific Rationale for Large-Class Missions Outside the Mars Exploration Program

One Flagship mission is recommended for this decade—the Europa Geophysical Explorer.

Europa Geophysical Explorer

Europa holds the most promise for increasing current understanding of the biological potential of icy satellites. Convincing evidence exists for the presence of liquid water within just tens of kilometers of the surface, and there is evidence for recent transfer of material between the surface and the water layer. Europa's ocean is probably in direct contact with a rocky mantle below and is potentially endowed with hydrothermal systems, so chemical disequilibrium may be able to nourish oceanic organisms. The first step in understanding the potential for icy satellites as abodes for life is a Europa mission with the goal of confirming the presence of an interior ocean, characterizing the satellite's ice shell, and understanding its geological history. Europa is important for addressing the issue of how far organic chemistry goes toward life in extreme environments and the question of how tidal heating can affect the evolution of worlds. Europa is key to understanding the origin and evolution of water-rich environments in icy satellites. **The SSE Survey endorses the current recommendations for a mission to orbit Europa. However, given the high cost of the Europa Geophysical Explorer mission, the Survey considers it essential that the mission address both the Group 1 and Group 2 science objectives described by the Europa Orbiter Science Definition Team.** These objectives are as follows:

- *Group 1.* Determine the presence or absence of an ocean; characterize the three-dimensional distribution of any subsurface liquid water and its overlying ice layer; and understand the formation of surface features, including sites of recent or current activity, and identify candidate landing sites for future lander missions.
- *Group 2.* Characterize the surface composition, especially compounds of interest to prebiotic chemistry; map the distribution of important constituents on the surface; and characterize the radiation environment in order to reduce the uncertainty for future missions, especially landers.

Flagship missions have been a traditional means for international cooperation in which NASA and other national space agencies, including the European Space Agency (ESA), can leverage their resources to accomplish what might otherwise be difficult to achieve. Galileo and Cassini-Huygens provide good examples in this respect, and **the SSE Survey recommends that NASA engage prospective international partners in the planning and implementation of the Europa Geophysical Explorer.**

Relative Priorities Between Mission Cost Classes

The SSE Survey did not attempt to prioritize across mission cost classes so that flexibility is preserved in order to address opportunities in the annual budget cycle. The opportunities to mount large-class missions are very limited, and if a lower-cost mission can be accommodated in a new budget cycle, it should not be thwarted by a requirement to wait for an opportunity to initiate a more expensive mission. **Rather than compete large-class missions with missions in other cost classes, the SSE Survey recommends flying large-class missions at an appropriate frequency (i.e., roughly one per decade), independent of the issues facing new starts in other cost classes.**

Since large-class missions represent an enormous investment and generally require a decade of study to mature in concept and design, **the SSE Survey recommends that NASA establish a procedure for reevaluating the candidate list of large-class missions for the decade 2013-2023. Two possible mechanisms for this procedure include (1) the appointment of a Science Definition Team every 3 years to define candidate missions or (2) a periodic competition for funds to support initial definition studies of missions concepts.** Some large-class missions identified by the SSE Survey for the 2013-2023 decade, and which should be revisited in the near future, are listed in Box 8.1.

BOX 8.1
Deferred High-Priority Flight Missions

The SSE Survey deemed the following mission concepts worthy of flight and accorded them a high priority. However, for reasons of mission sequencing, technological readiness, or budget, they did not make the final cut for the coming decade:

Medium Class
Geophysical Network Science
Trojan/Centaur Reconnaissance Flyby
Asteroid Rover/Sample Return
Io Observer
Ganymede Observer

Large Class
Europa Lander
Titan Explorer
Neptune Orbiter with Probes
Neptune Orbiter/Triton Explorer
Uranus Orbiter with Probes
Saturn Ring Observer
Venus Sample Return
Mercury Sample Return
Comet Cryogenic Sample Return

The Kuiper Belt-Pluto Explorer is the first priority in the medium-cost class, and the Europa Geophysical Explorer (EGE) mission is the first priority in the large-cost class. The Kuiper Belt-Pluto Explorer mission, with its potential for creating a new paradigm regarding primitive processes in the outer solar system and their effect on the evolution of bodies in other parts of the solar system, has scientific merit similar to that of the EGE mission, which seeks primarily to define a possible habitat for life by vastly expanding our current knowledge of a subsurface ocean. With respect to technical readiness and special opportunities the Kuiper Belt-Pluto Explorer mission has clear advantages over EGE.

Deferred High-Priority Missions

The prioritization process forces the SSE Survey to defer what would otherwise be excellent high-priority missions worthy of flight. Box 8.1 lists mission concepts that are among the highest-ranked by the SSE Survey's panels, but that did not make the final recommended priority list for the coming decade.

Some of these missions are deferred because their science objectives can be more precisely defined after precursor missions are flown. The Europa Lander should follow as the next step after the Europa Geophysical Explorer. Similarly, a Titan Explorer mission should follow Cassini-Huygens. After having conducted orbiter missions to the two gas giants, Jupiter (Galileo) and Saturn (Cassini), an orbiter mission to an ice giant should follow—the highest-rated being a Neptune orbiter mission carrying deep atmosphere (100-bar) probes with special attention to Triton exploration through flybys and perhaps a lander. These outer-planet missions will be enhanced and enabled by advanced nuclear power and propulsion. Venus sample return should follow after experience with lunar and martian sample return, and a cryogenic comet sample return should follow experience with a non-cryogenic sample-return mission. The proposed set of medium-class/New Frontiers missions should be revisited on an appropriate time scale as new discoveries are made in the course of the solar system exploration enterprise.

PRIORITIES FOR THE MARS EXPLORATION PROGRAM

The exploration and scientific investigation of Mars have reached an important stage. Exciting discoveries from recent successful missions and the ongoing research and analysis of data from these missions and martian meteorites have established a broad understanding of the planet and its evolution. These developments have also raised a number of fundamental and compelling questions related to all aspects of Mars, from the outer atmosphere and space environment to the deep interior. The sheer number of questions presents a challenge to establishing a rationale and a fiscally prudent plan that moves toward addressing the highest-priority question identified by numerous bodies (e.g., COMPLEX, MEPAG, and this survey): Did life ever arise on Mars? No single measurement at a specific location on Mars will answer this question. Nor is the importance of the question understood without a broad understanding of Mars's current processes and past evolution.

It is imperative that the exploration of Mars move aggressively to surface missions for in situ science investigations and that it lay the foundation for sample return, the latter beginning early in the decade 2013-2023. In situ science is progressing rapidly, and such investigations will add substantially to our knowledge across a broad range of disciplines for Mars. However, the results that will flow from the detailed investigations of martian samples returned to Earth using modern techniques and sophisticated equipment will simply dwarf all previous results. It is important to be aware that the first samples returned from Mars may not be definitive regarding the life question, no matter how carefully the samples are selected. However, the first returned samples would establish beyond a shadow of a doubt how the exploration of Mars must proceed and where to explore, using in situ measurements and additional returned samples. Equally importantly, these samples will forever change our understanding of geologic and climate evolution, surface-atmosphere interactions, and Mars as an abode of life.

Table 8.1 above contains the prioritized list of missions for the future Mars Exploration program, and Table 8.2 indicates a possible mission sequence for their implementation.

Recommended Mars Missions

Mars Sample Return

Observations by robotic orbiters and landers alone are not likely to provide an unambiguous answer to the most important questions regarding Mars: whether life ever started on that planet, what the climate history of the planet was, and why Mars evolved so differently from Earth. The definitive answers to these questions will require analysis in Earth-based laboratories of Mars samples returned to Earth from known provenances on Mars. Moreover, samples will provide the ultimate ground-truth for the wealth of data returned from remote-sensing and in situ missions**. The SSE Survey recommends that NASA begin its planning for Mars Sample Return missions so that their implementation can occur early in the decade 2013-2023.**

The Need for Sample Return to Search for Life. At our present state of knowledge and technological expertise, it is unlikely that robotic in situ exploration will be able to prove to an acceptable level of certainty whether there

TABLE 8.2 A Possible Sequence for Future NASA Mars Science Missions with Early Sample Return

Year of Launch				
2005	2007	2009	2011	2014
Mars Reconnaissance Orbiter	Mars Scout 1	Mars Science Laboratory	Mars Scout 2	Mars Sample Return with international partners

once was or is now life on Mars. Results obtained from life-detection experiments carried out by robotic means can be challenged as ambiguous for the following reasons:

- Results interpreted as showing an absence of life will not be accepted because the experiments that yielded them were too geocentric or otherwise inappropriately limited;
- Results consistent with but not definitive regarding the existence of life (e.g., the detection of organic compounds of unknown, either biological or nonbiological, origin) will be regarded as incapable of providing a clearcut answer; and
- Results interpreted as showing the existence of life will be regarded as necessarily suspect, since they might reflect the presence of earthly contaminants rather than of an indigenous martian biota.

The Need for Sample Return for Geochemical Studies and Age Dating. Rocks contain a near-infinite amount of information on a microscopic scale, some of it crucial to an understanding of the rock's origin and history. The constituent minerals, fluid inclusions, and alteration products can be studied chemically and isotopically, providing critical information on the age, dates of thermal and aqueous alteration events, nature of the source regions, and history of magmatic processes. In situ instrumentation will always be limited to a fraction of the potential measurement suite and lower levels of precision and accuracy. Information about the Mars climate will be found in the layer of weathering products that we expect to find on rock samples and in the soils. These products will almost certainly be very complex minerals or amorphous reaction products that will tax our best Earth-based laboratory techniques to understand. A critical unknown for Mars is the absolute chronology of the observed surface units. Precise and accurate dating of surfaces with clearly defined crater ages is best accomplished with returned samples.

The Need for Sample Return for Studies of Climate and Coupled Atmosphere-Surface-Interior Processes. Key measurements in modeling the relative loss of portions of the atmosphere to space and to surface reservoirs are surface mineral compositions and their isotopic systematics. Atmospheric loss processes (e.g., hydrodynamic escape, sputtering) leave characteristic isotopic signatures in certain elements. Loss to space and surface weathering (e.g., CO_2 to carbonate minerals) are likely to produce isotopic fractionation in different directions. $^{15}N/^{14}N$ in the martian atmosphere is understood to have evolved over the past 3.8 billion years (it is currently 1.6 times the terrestrial value), and a determination of this ratio in near-surface materials may constrain the time of their formation. Compositional and isotopic analysis of surface minerals, weathering rinds, and sedimentary deposits will establish the role of liquid water and processes such as weathering. The corresponding measurements on volatiles released from near-surface materials are likely to be more heterogeneous and may provide fossils of past atmospheric and chemical conditions that allow the past climate to be better understood.

The SNC Meteorites Do Not Obviate the Need for Sample-Return Missions. SNC meteorites have provided a tantalizing view of a few martian rocks and a demonstration of how much can be learned when samples can be examined in Earth-based laboratories; however, they represent a highly selected subset of martian materials, specifically, very coherent rocks of largely igneous origin from a small number of unknown locations. Thus, SNC meteorites are unhelpful in answering one of our outstanding questions—What is the absolute chronology of Mars?—because although these meteorites can be accurately dated, the geologic units from which they are derived are unknown. While returned samples are also a selected subset of martian materials, we will know their geologic context, and they will be from sites selected because they can provide particularly valuable information.

Mars Science Laboratory

The Mars Science Laboratory (MSL) is an important mission along the path of "Seek, in situ, and sample." The science goals are to conduct detailed in situ investigations of a site that is a water-modified environment identified from orbital data. As such, this mission will provide critical ground-truth for orbital data and test hypotheses for the formation and composition of water-modified environments identified through morphological and spectroscopic investigations. The types of in situ measurements possible on MSL are wide ranging, including atmospheric sampling, mineralogy and chemical composition, and tests for the presence of organics. There currently is some debate as to whether this mission will have roving capability on the order of 10 km, or be more focused toward drilling to get below the surface, which is hostile to life. Both strategies have merit in addressing high-priority science goals, though the drilling mission puts a much greater demand on precision landing. Regardless of the ultimate design of the instrumentation, **the SSE Survey recommends that while carrying out its science mission, the Mars Science Laboratory mission should test and validate technology required for sample return (e.g., sample handling and storage in preparation for sample return and feed-forward lander design, consistent with the future use of a Mars Ascent Vehicle).** In addition, the surface operations of the Mars Science Laboratory mission should feed forward to Mars Sample Return.

Mars Scout Program

Mars Scout provides an excellent opportunity for NASA to address science priorities outside the principal objectives of the Mars Exploration Program, and for the broad science community to respond to discoveries and technological advancement. **The SSE Survey recommends that the Mars Scout program be managed as is the Discovery program, with principal-investigator leadership and competitive selection of missions.** It is essential, therefore, that the measurement goals for the Mars Scout program be directed toward the highest-priority science for Mars and be selected by peer review. The missions-of-opportunity element of the Scout program is also important, as it allows for participation in foreign Mars missions. **The SSE Survey strongly recommends that the Mars Exploration Program commit equally as strongly to the Scout program as to sample return.**

While Mars sample-return missions will be expensive and consuming of the attention of the MEP, there are sufficient resources in the program as currently structured to achieve both a viable Scout program and sample return. As witnessed by the response to the recent call for Scout proposal ideas (over 40 submissions were received), tremendous enthusiasm has been stimulated by recent Mars discoveries and scientific investigations not covered by the MEP. Scout provides a mission component that is highly flexible and responsive to discovery. **The SSE Survey recommends that a Mars Scout mission be flown at every other launch opportunity.**

Mars Long-Lived Lander Network

The SSE Survey's Mars Panel considers that a long-lived network of landed science investigations (ML^3N) should be a high-priority Mars mission. The principal experiments on these landed stations should be passive seismometers to determine interior structure and activity, and analyzers of the ground-level atmosphere to address areas of importance to martian atmospheric science (meteorology, atmospheric origin and evolution, chemical stability, and atmospheric dynamics). Both the seismological and atmospheric measurements must continue to record data for at least 1 martian year to achieve their potential. NASA advisory panels have consistently recognized the importance of these experiments and recommended their implementation.[2] These questions are of particular interest for a broad community of scientists, because useful comparisons with Earth can be made that may prove important for understanding the atmospheric evolution of both planets. Network science has been identified by the European Space Agency as a priority for Mars (the NetLander mission).

Mars Upper Atmosphere Orbiter

The SSE Survey includes in its priority scheme an orbiter dedicated to studies of Mars's upper atmosphere and plasma environment. Interactions with the solar wind are thought to have played a significant role in the long-term evolution of the martian atmosphere, yet no measurements have been made to confirm or reject these ideas. A variety of atmospheric escape processes have been inferred from indirect measurements and/or predicted from theoretical models. This mission would provide quantitative information on the various potential escape fluxes and, thus, quantify current escape rates. Back extrapolation of such measurements might result in new understanding of the evolution of the martian atmosphere and maybe also provide important clues to atmospheric evolution on Venus and Earth. In carrying out these measurements, numerous other important questions of high scientific value associated with the middle and upper atmosphere, exosphere, ionosphere, and solar-wind interaction processes will also be addressed.

No plans exist in the current U.S. Mars Exploration Program to address any of the scientific questions identified by previous panels in this area. The Nozomi and Mars Express missions will address them to some extent, but much more data will be needed to meaningfully elucidate these issues. The measurements required for this mission could be accommodated as a science package on an international orbiter mission or as a stand-alone mission in the Mars Scout program.

Staging, Sequencing, Links to Other Mars Missions, and International Partnerships

Developed in 1999 after the failures of Mars Polar Lander and Mars Climate Orbiter, the Mars Exploration Program is founded on the pursuit of the highest-priority investigations along the path of "Seek, in situ, and sample." The "Seek" component consists of orbital investigations to identify sites with remotely sensed signatures indicative of water. The "in situ" component involves getting to the surface for detailed characterization of specific sites and providing ground-truth for orbital measurements. Finally, the "sample" component concerns the return to Earth of pieces of Mars that will be important for addressing the life question as well as all other aspects of martian science.

The MEP plans for a mission to Mars at every launch window (approximately once every 2 years) and is cost-constrained to some $700 million per opportunity. The program is designed to be flexible and responsive to discoveries, though mission design and implementation cycles require that the science objectives and instrument suite for the next opportunity be fixed prior to the results derived from the current opportunity.

The Mars Exploration Program is currently reevaluating future missions, principally in response to the high cost of sample return. The program is being directed to develop discovery-driven investigation pathways with missions at every opportunity, unless compelling scientific justification can be developed for sample return. The SSE Survey believes that sufficient resources exist in the Mars Exploration Program to achieve the highest-priority mission identified by this and other panels (COMPLEX, MEPAG, and so on) while maintaining a flexible and discovery-driven program of Mars exploration. Furthermore, this can be achieved to allow the first sample-return mission early in the next decade (2013-2023). As an example, one possible pathway with an early sample return is outlined in Table 8.2. The interleaving of Mars Scout with other MEP missions maintains the discovery-driven aspects of the program. It is important to recognize that MSR will be a long mission from development, through launch, sample return, and sample analysis. It will take some time after the samples return to Earth for the results of the analyses to be integrated with previous Mars knowledge. Additionally, sample containment and curation facilities must be operational before samples are returned, as was emphasized earlier in this report.

The SSE Survey advocates that MSL be structured to accomplished high-priority science goals and to achieve technological advances necessary for sample return. Sample-return technology can also be leveraged from developments in other missions, most importantly the lunar South Pole-Aitken Basin Sample Return mission, recommended as a priority for the New Frontiers program. There are likely many common elements between this mission and MSR, for example, the ascent vehicle, orbital rendezvous, landing systems, and sample handling and receiving. In fact, the opportunity to test the Earth-return aspects of sample handling without the high-level planetary protection protocols required for MSR might be a critical test of the technologies required for MSR.

Countries other than the United States are keenly interested in Mars exploration and have committed significant resources to national and international programs. Many of these countries have expressed a willingness to participate in NASA's efforts, and several joint efforts are currently under way. The SSE Survey advocates that NASA actively pursue international collaborations such as Missions of Opportunity on European orbiters and landers. **The SSE Survey recommends that NASA engage prospective international partners in the planning and implementation of Mars Sample Return at an early stage in order for this complex mission to benefit fully from the capabilities and resources offered by the international community.**

ADVANCED TECHNOLOGY

Technology Development

The SSE Survey recommends that NASA commit to significant new investments in advanced technology so that future high-priority flight missions can succeed. Unfortunately, erosion has occurred in the level of investment in technology in the past several years. Flight-development costs have increased over projections, and investments in advanced technologies have been redirected to maintain flight-mission development schedules and performance.

For most of the history of planetary exploration, large-cost flight missions such as Voyager, Viking, Galileo, and Cassini have carried a large portion of the technology-development burden in their development costs. During the change in the last decade to a larger number of lower-cost flight missions, the consequent loss of technology development by large missions was compensated by adding separate technology-development cost lines to the planetary exploration portfolio, such as X2000, under an understood policy of "no mission start before its technological time." This mechanism was intended to separate and remove the uncertainties in technological development from early flight-development costs. However, flight-mission costs have been underestimated, and development plans have been too success-oriented, resulting in erosion of technology-development lines by transfer to flight-development costs. This trend needs to be reversed in order to realize the flight missions recommended in this report.

This report identifies a clear set of missions for development in the next decade, providing a compelling focus for advanced technology development. NASA must maintain this focus, even as it increases competition in technology development, to ensure long-term stability and strong coordination with flight-mission needs.

Generic Technologies

Generic technologies exist that will benefit almost every flight program. To focus technology development on the most important needs for the next decade, the SSE Survey identified the most enabling technologies for key interplanetary spacecraft subsystems—power, propulsion, communication, architecture, avionics, and instrumentation—and for planetary surface exploration—entry, in situ systems, surface mobility, communications, and Earth-return systems (Table 8.3).

The two most-constrained resources in the current generation of planetary spacecraft are onboard power and propulsion. Improvements in these two areas will enable the largest leaps forward in capability. Solar power is generally insufficient beyond the asteroid belt, provides limited power for spacecraft systems, and severely limits the lifetime of landed spacecraft. Most solar-powered planetary spacecraft have only a few hundred watts of

TABLE 8.3 Recommended Technology Developments

Category	Recommended Development
Power	**Advanced radioisotope power systems, in-space fission-reactor power source**
Propulsion	**Nuclear-electric propulsion, advanced ion engines, aerocapture**
Communication	**Ka band, optical communication,** large antenna arrays
Architecture	**Autonomy,** adaptability, lower mass, lower power
Avionics	**Advanced packaging and miniaturization,** standard operating system
Instrumentation	**Miniaturization,** environmental tolerance (temperature, pressure, and radiation)
Entry to landing	**Autonomous entry, precision landing,** and hazard avoidance
In situ operations	Sample gathering, handling, and analysis; drilling; instrumentation
Mobility	**Autonomy;** surface, aerial, and subsurface mobility; hard-to-reach access
Contamination	Forward-contamination avoidance
Earth return	**Ascent vehicles,** in-space rendezvous, and Earth-return systems

NOTE: Bold type indicates a priority item.

power available for science. In-space chemical propulsion has limited capability, especially for missions to the outer planets, resulting in very long flight times and often limiting missions to rare launch windows requiring multiplanet flybys to gain the necessary energy. The solution to the power and propulsion problems is development of advanced nuclear power sources and in-space nuclear-electric propulsion. Advanced radioisotope power systems (RPSs) are required to replace the depleted inventory of first-generation RPSs. Advanced RPSs are required for both spacecraft power and for early low-power versions of in-space nuclear-electric propulsion (NEP). Finally, a compact and efficient (high thrust-to-mass ratio) flight-qualified nuclear-fission reactor should be developed in parallel with the development of second- and third-generation ion drives for the high-power NEP systems required to reach the outer solar system. Development of aerocapture as a means to reduce in-space propulsion requirements will significantly improve mission performance to all planets with atmospheres.

The SSE Survey is highly supportive of NASA's nuclear power and in-space nuclear propulsion initiative. The Survey believes that in the second half of this decade this program can produce advanced flight-qualified RTGs that could be flown on the Europa Geophysical Explorer and Jupiter Polar Orbiter with Probes, and on the Mars Science Laboratory. The development of in-space NEP, including its first qualification flight in space, will take almost the entire decade and will become available for advanced outer-planet missions at the beginning of the next decade. The outer-planet missions recommended for flight in this decade (e.g., the Kuiper Belt-Pluto Explorer) can be accomplished without NEP.

The development of nuclear technologies, while clearly enabling for many planetary missions, will be controversial in their application and in the public mind. This new initiative was announced too late for the SSE Survey to assemble all the required expertise and to consider all the ramifications of the proposal. The fission-based technology will take a decade to develop in any case, so the Survey devised a flight program for the next decade that does not require it. In the meantime, **the SSE Survey recommends that a series of independent studies be undertaken immediately to examine the scientific, technical, and public issues involved in the use of nuclear technologies on planetary spacecraft.** A science study should be conducted to determine which mission types are enabled by nuclear technologies and which are not. An engineering study should be undertaken to consider the design and safety aspects of the proposed nuclear technologies. And, a study should be conducted to examine public attitudes toward this technology, how to provide the public with an understanding of the issues, and means for mitigating public acceptance problems that are due to fear and misunderstanding of these issues.

In the area of spacecraft communications, it is assumed that current development of Ka-band capability and antenna arrays will mature in the early years of this decade. The next most important step is the development of optical communications for a major leap forward in communications bandwidth, particularly for video-rate communications from Mars and for advanced exploration in the outer solar system. **Advanced optical and/or radio communications should be developed and flight-qualified toward the end of this decade for use by Mars Sample Return and the next generation of outer-planet missions powered by NEP.**

In the area of spacecraft systems, the key demand is for considerable autonomy and adaptability through advanced architectures. Lower-power, lower-mass spacecraft need to be developed commensurate with realistic cost and performance for the available expendable launch vehicles. Not unrelated is the need for more capable avionics in a more highly integrated package through advanced packaging and miniaturization of electronics and with a standardized software operating system.

New and increased science measurement capability in planetary science instruments and greater environmental tolerance will be required for less mass and power. Miniaturization is the key to the reduction of mass and power requirements. For the inner solar system, electronics tolerant to extremes of temperature (both hot and cold) are required. High-temperature, corrosion-resistant, and pressure-tolerant systems are required for in situ exploration on Venus. For the outer planets, radiation-hard electronics, shielding, tolerance, and reliability are required.

As planetary exploration moves into the new century with more in situ and sample-return missions, it will be necessary to develop planetary landing systems, in situ exploration systems, and Earth-return technologies. The key requirements for landing systems are autonomous entry, descent, hazard avoidance, and precision landing systems. Once on the surface, sample gathering and analysis become key technologies, with attendant requirements for new surface science instruments, including biological measurements, and means for moving about a planet—on, above, and below the surface. Systems for accessing difficult-to-reach areas will be required.

Rover technology should advance toward long-life and long-range capability, with autonomous hazard avoidance and the ability to operate on large slopes. Drilling techniques on both terrestrial and icy surfaces will be needed, advancing toward deep-ice penetration and submarine exploration in subsurface oceans. Aerial platforms for Mars and Venus will be required; they will be the forerunners of systems to be deployed on Titan and the outer planets. Advanced autonomy will need to be built into all of these mobile mechanisms.

The means to return planetary samples needs to be developed, beginning with small bodies and the Moon, advancing toward Mars, then Venus, and eventually to more distant targets such as Mercury and the satellites of the outer planets. Some recommended missions will be sent to planets and satellites that are targets for biological exploration and will require meeting planetary protection requirements related to forward and back contamination. Technologies will be required to meet these requirements while reducing the costs to do so.

Mission-Specific Technologies

In addition to the generic technologies described above and summarized in Table 8.3, mission-specific technologies are required for the flight missions selected for this decade. They are described below.

Kuiper Belt-Pluto Explorer

The Kuiper Belt-Pluto Explorer mission is ready now, has no requirements for new technology, and can use one of the few remaining first-generation RPSs This is a multiple-object flyby mission designed as the first reconnaissance of a number of Kuiper Belt objects, including the largest and best studied example, Pluto-Charon. It is premature to consider an orbiter for any of these objects. For this reason, and because of the low relative flyby velocities required and the requirement to reach Pluto at the earliest possible date, an NEP option with the necessary advanced ion engines is not appropriate. There is no confidence that both can be developed in time, nor are they necessary for this mission. Consideration should be given, however, to the use of a solar-electric propulsion stage to avoid reliance on a singular Jupiter gravity-assist opportunity in 2006.

Europa Geophysical Explorer

Radiation-hard electronics is the key requirement in addition to the generic technologies for outer-planet missions given above. This mission is focused almost exclusively on Europa, where it is much easier to confirm the existence of a subsurface ocean and to determine its extent than it is at Ganymede or Callisto. This orbiter mission would not benefit significantly from NEP because of the strong focus on a single object with a limited set of scientific measurements. Once confirmed on one Galilean satellite, a follow-on mission might be considered using an NEP spacecraft to consecutively orbit all three outer Galilean satellites to search for the extent of subsurface oceans and to dispatch landed probes.

South Pole-Aitken Basin Sample Return

The SPA-SR mission to the farside of the Moon could be the first test of sample-return technologies to be used on Mars. The developments required for these missions are very nearly the same, except for the system for braking from orbit. The common elements are automated descent; hazard avoidance and precision landing; advanced in situ sampling, perhaps even drilling; advanced in situ instrumentation, including radiometric age-dating and chemical and mineralogical analysis; sample transfer; and an ascent vehicle and Earth-return system. A means for communication with a lunar farside station will be required. A successful SPA-SR mission will provide early demonstration of planetary sample-return technology without the need for planetary protection and will significantly reduce the risk for a Mars sample-return mission.

Jupiter Polar Orbiter with Probe

The JPOP mission will require advanced RPSs, radiation-hard avionics, and the revival of the Jupiter entry-system technologies first developed in the 1970s. The probes should survive and be in communication to 100 bars, whereas the signal from the Galileo probe was lost at 22 bars. Lightweight mass spectrometers for sampling at high pressures with internal gas processing for complex analysis are the key science instrument technology. The deep probes developed for this mission will then be available for similar missions to the other giant planets, Saturn, Uranus, and Neptune. NEP is not required for this mission.

Venus In Situ Explorer

The key technologies for the VISE mission are those for system survivability, shallow drilling, sample acquisition, and sample transfer at extreme high temperature and pressure in a corrosive environment; high-temperature balloon materials; and long-lived compact power sources. The mission will require in situ instruments that can survive the Venus surface environment and that can accomplish radiometric age-dating and chemical and mineralogical analysis of surface samples while at altitude. The use of advanced solar-electric propulsion coupled with aerocapture would markedly increase the performance of this mission.

Comet Surface Sample Return

The key technology required for the CSSR mission is a sample-acquisition system without significant on-surface time, drilling, or sample manipulation and storage at cryogenic temperatures. Advances in automation, ion propulsion, and solar- and/or nuclear-power sources will improve the performance of this mission.

Mars Missions

In addition to the generic orbital, in situ, and sample-return mission technologies listed above, for which Mars is a prototypical benefactor, planetary protection technologies (both forward and back) and attendant sample containment, Earth return, and handling and examination facilities are the key technical issues to be addressed. A Mars-Earth return system, including an ascent vehicle and in-space rendezvous and sample capture, are key technologies that can evolve from the vehicles developed for the South Pole-Aitken Basin Sample Return mission.

Technologies for the Following Decade

Technology development necessarily precedes flight-mission development, and the technologies developed for this decade must evolve into the technologies required for missions early in the next decade. The most important of the technologies developed in this decade for use in the next are advanced in-space NEP and spacecraft nuclear power systems. These power and propulsion technologies will enable missions that cannot otherwise be accomplished. NEP will reduce or eliminate the need for gravity assist, enable launch in any year, yield shorter trip times for many types of missions, reduce launch vehicle requirements, enable tours of many different destinations on the same mission, and enable outer-planet orbiters with long life, propulsion for extensive system touring, high power output, and significantly larger payloads. Active remote-sensing instruments, including synthetic-aperture radar and laser-activated techniques, will be enabled by fission power sources.

Examples of missions following naturally in the next decade from those recommended in this decade, and which are enabled or enhanced by NEP, include a Neptune Orbiter carrying Neptune atmospheric probes and Triton surface probes, a Titan Explorer mission carrying an aerial vehicle and landers for Titan, and a Saturn Ring Observer for maneuvering above Saturn's ring plane. The addition of aerocapture technology to these missions will yield a combination of enhanced capabilities, reduced launch vehicle requirements, and/or reduced in-space propulsion system requirements.

Optical communications, including advanced science instrumentation to utilize the increased bandwidth, should be available for missions in the next decade. The perfection of Mars sample-return technology should be followed by its adaptation for return of samples from the surface of Venus. Drilling and cryogenic sampling will be required for the return of a completely preserved core sample of a comet nucleus. Aerial vehicles will be required for the exploration of Titan, Mars, and Venus; subsurface vehicles for Mars and perhaps Europa; and complex organic chemistry and microbiology laboratory packages for exploring organic-rich environments, including Europa and Titan and perhaps even subsurface aquifers of Mars. Long-lived, high-temperature, and high-pressure systems will be required for Venus sample return and surface stations such as seismic networks.

The Deep Space Network

The Deep Space Network (DSN) is suffering from insufficient communications capability and occasional failures as it ages. Limitations on downlink bandwidth restrict the return of data from spacecraft ranging from some Discovery flights (e.g., the Deep Impact encounter sequence requiring real-time links) through the Flagship Cassini mission (constrained by the feeble signal from distant Saturn). While efforts to increase the transmitter power on spacecraft are valuable, likely it will be less expensive to augment both transmitter power and communications capacity on Earth than to correspondingly increase these factors on all spacecraft. Furthermore, additional ground stations would be valuable to provide geographic redundancy for the system as a whole, and they would grant more freedom in the timing of critical spacecraft events. Studies should consider whether it is better to move toward shorter wavelengths such as Ka band, toward very large collecting areas, or toward optical communication links. Studies should also examine the efficiency gains that might be realized by using a packet-switched network protocol for communicating with a large number of planetary spacecraft.

The SSE Survey recommends upgrades and increased communications capability for the DSN in order to meet the specific needs for this program of missions throughout the decade, and that this be paid from the technology portion of the Supporting Research and Technology (SR&T) line rather than from the mission budgets. While it is perfectly reasonable, under full cost accounting, to use a straightforward algorithm that assesses costs for operating the DSN to specific missions, any upgrade cannot realistically be charged to the first mission that uses it, and an amortization schedule would be entirely ad hoc given the uncertain number of prospective client missions that might employ the DSN. Such a voluntary system of payment would make the financial status of the entire upgrade program unstable, since the program would be subject to the financial decisions of individual mission managers.

EARTH-BASED TELESCOPES

NASA currently provides support, in widely varying percentages, for planetary science operations at Arecibo, Goldstone, Keck, and the Infrared Telescope Facility, in collaboration with the National Science Foundation (NSF), DSN, a private consortium, and NSF, respectively. As described in Chapter 6 of this report, these facilities have made major contributions both to planetary science in general and to specific flight missions. The IRTF, the only facility dedicated to NASA planetary astronomy, has provided vital data in support of flight missions. **The SSE Survey recommends that the planetary radar facilities, the Infrared Telescope facility and NASA support for planetary observations at large facilities such as Keck be continued and upgraded as appropriate, for as long as they provide significant scientific return and/or provide mission-critical service.**

The recent so-called Augustine report urged that NASA and NSF collaborate in astronomy in order to coordinate their efforts and produce the best science for the national investment.[3] In particular, that report's second recommendation urged the federal government "to develop a single integrated strategy for astronomy and astrophysics research that includes supporting facilities and missions on the ground and in space."[4] The SSE Survey notes, however, that developing such a single, integrated strategy for planetary astronomy will not be easy. While NASA's support for the Keck and IRTF facilities on Mauna Kea has been enthusiastic and substantial, there appears to be growing reluctance to fund some kinds of ground-based astronomical research. Similarly, NSF has provided very limited support for planetary science in recent years, a situation that is particularly unfortunate, given NSF's charter to support the best science and its leadership role in other aspects of ground-based astronomy.

While the SSE Survey presumes that the Solar System Exploration program's current collaborations with NSF and private consortia will continue as long as they are scientifically productive and relevant to NASA's missions, it notes that the coming decade presents a nearly unique opportunity to develop better coordination and collaboration, particularly in light of significant overlap between recommendations of this survey and those of the 2001 astronomy and astrophysics decadal survey.[5]

In the spirit of the Augustine report's second recommendation, **the SSE Survey recommends that NASA partner equally with the National Science Foundation to design, build, and operate a survey facility, such as the Large Synoptic Survey Telescope (LSST) described in *Astronomy and Astrophysics in the New Millennium*, to ensure that LSST's prime solar system objectives are accomplished.** The particular planetary objectives of LSST are as follows:

- Determine the contents and nature of the Kuiper Belt to provide scientific context for the targeting of spacecraft missions to explore this new region of the solar system;
- Assess the population of near-Earth objects (NEOs) down to 300-m in diameter and provide a measure of the impact hazard; and
- Ascertain the relative importance of long-period comets as impact hazards to Earth.

The LSST (Figure 8.1) will also assess the distribution of Centaurs and search for uranian and neptunian Trojans. Such a facility has been separately recommended by the most recent astronomy and astrophysics decadal survey.[6] The latter report lists NEO detection and Kuiper Belt object surveys as LSST's two top science drivers, followed by a host of astrophysical applications. Indeed, the parameters of the LSST are largely determined by the need to detect NEOs, since this is the most difficult measurement to make with the telescope.

The design of missions to the small bodies of the solar system requires extensive physical characterization of a significant subset of these objects in order to properly choose the best targets to answer particular scientific questions. This physical characterization is best done with telescopes having a suite of instruments for imaging and spectroscopy at various wavelengths. While the brighter of the small bodies of the solar system can be readily studied with what are now thought of as small to medium telescopes, the fainter members of the Kuiper Belt, which are orders of magnitude more numerous than the bright members, cannot be characterized with existing facilities.

Similarly, assessment of the hazard from NEOs requires physical characterization of the ensemble by remote sensing in order to carry out the missions to investigate more detailed physical characteristics in situ. As with the Kuiper Belt objects, the fainter NEOs and long-period comets require a very large telescope for physical characterization.

The high-angular-resolution capability of large ground-based telescopes equipped with adaptive optics (AO) now surpasses that of telescopes in space. For example, the Keck and Gemini telescopes routinely achieve angular resolutions better than 50 milliarcseconds (mas) at near-infrared wavelengths. Planned ground-based telescopes will have resolutions better than 10 mas. At this resolution, the disks of Jupiter and Neptune can be resolved into 10^7 and 4×10^4 resolution elements, respectively, opening the intriguing possibility for long-term studies of atmospheric dynamics and spectroscopy from the ground. Spectroscopy of the giant planets is crucial for understanding the altitude variations of their atmospheric properties.

The requirements of a telescope capable of performing the physical characterization of small solar system bodies described above—a 30-m-class, fully steerable facility equipped with adaptive optics—are similar to those of the Giant Segmented Mirror Telescope (GSMT) as proposed by the 2001 astronomy and astrophysics decadal survey (Figure 8.2).[7] This telescope will allow characterization of 10-km bodies in the Kuiper Belt and allow targeted searches for 1-km objects that are inaccessible by other means. It will permit continuous study of the atmospheres of the planets as a precursor and complement to the missions prioritized in this report. The planetary community should be fully involved in defining the capabilities of the GSMT, including its all-important AO system and the specific instruments that will be developed for this telescope.

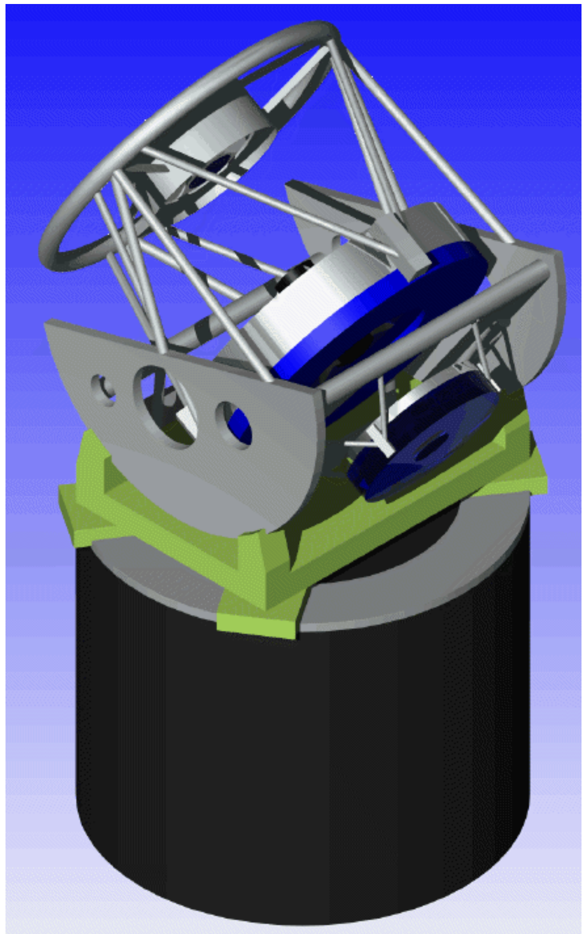

FIGURE 8.1 An artist's impression of one particular concept for the Large Synoptic Survey Telescope. Courtesy of the National Optical Astronomy Observatories.

The SSE Survey endorses the 2001 astronomy and astrophysics decadal survey recommendation for a Giant Segmented Mirror Telescope and further recommends that it be utilized for the physical characterization of solar system objects.

The track record of contributions to solar system exploration by Earth-orbital missions sponsored by the other themes at NASA has been exceptional and was made possible only by ensuring that those facilities have an appropriate capability to track moving targets. The James Webb Space Telescope (JWST) clearly has the capability to make major contributions as long as it is provided with the capability to track moving targets. **The SSE Survey recommends that capabilities particular to planetary science (e.g., the need to track non-sidereal objects) be incorporated into the James Webb Space Telescope as fully as possible in order to maximize the science return.**

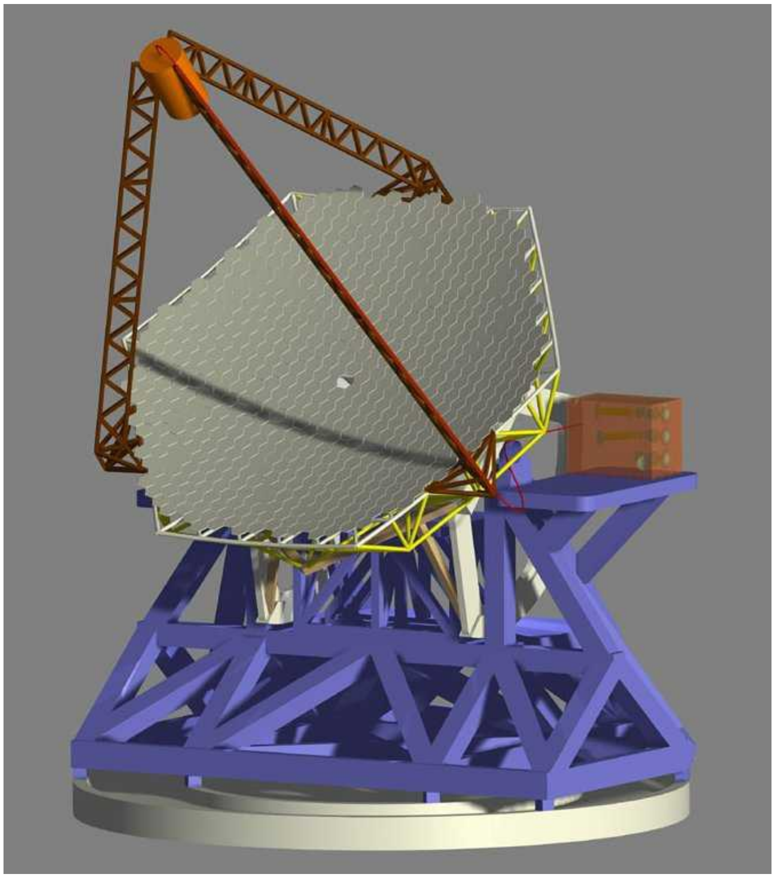

FIGURE 8.2 An artist's concept of one particular configuration for the proposed Giant Segmented Mirror Telescope. Courtesy of the National Optical Astronomy Observatories.

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Epilogue

A Glimpse at the Future of Solar System Exploration

The road that leads to the future of any endeavor is usually well defined only at its start. Quickly, the future becomes obscured by latent uncertainties: the possibility of new discoveries, changing paradigms, changes in national policy, blind alleys, and funding pleasures and disappointments. Solar system exploration is no exception.

Throughout most of its study, the SSE Survey focused on understanding the current status of solar system exploration and, to the best of its ability, determining the optimum direction for solar system exploration into the future. This is embodied in the system of priorities presented in Part Two. But where this road will eventually lead in the more distant future is difficult to forsee for all of the above reasons. Nevertheless, the Survey does have significant expectations that are worth discussing briefly here and that may have value for long-term planning.

THE COMPLEXITY OF THE INITIAL VECTOR TOWARD THE FUTURE

Four decades of steady progress made possible by increasingly capable missions supported by programs of Earth-based observations, individual research, interpretational data analysis, and technological development are clearly paying off. Our understanding of the origins, evolution, and nature of planets and moons, and of asteroids and comets, is now much improved over the more superficial view of the late 1950s, as is our knowledge of many of the specific physical and chemical processes characteristic of these bodies. Rapid advances have brought us to the point that a major investment in sample-return missions, for example, Mars exploration, is now anticipated. Recent telescopic discoveries have opened up new frontiers for understanding processes in the primitive solar system, for example, in the outer solar system beyond Neptune, for which vigorous reconnaissance by robotic spacecraft is the most appropriate strategy. As a result, contemporary priorities reflect a complex mix of mission types, technological demands, and research objectives, all with high scientific merit but with widely differing technical readiness and expectations for completion. This complexity is at the root of the difficulties in predicting future outcomes of the exploration program.

ANTICIPATION OF NEW DISCOVERIES

All missions currently flying or being prepared for flight and allied ground-based research projects, both in the United States and internationally, will undoubtedly lead to new and unpredictable discoveries, which is the nature of exploratory projects. Discovery is the essence of exploration. Taken together, missions such as Rosetta, Stardust, and Deep Impact can be expected to have a revolutionary effect on our understanding of the role of comets in how giant planets are seeded and the origins of primitive organic materials and volatiles and their distribution throughout the solar system. In addition, research in closely related fields such as the search for and characterization of planetary systems around other stars or the study of protostellar disks and early stellar evolution, programs that are strongly supported by the astrophysics community, will also yield results at unpredictable times in the future that will demand changes in the paradigm for solar system formation and thereby could change how solar system exploration is pursued, particularly for the giant planets and Kuiper Belt objects. The mission priorities offered in this survey are a good example of such influences, for they very much reflect discoveries of the recent past. The Kuiper Belt-Pluto Explorer that the SSE Survey advocates so strongly today would have been an unlikely candidate a decade ago, before the ground-based discovery of large numbers of Kuiper Belt objects exhibiting a fascinating variety of physical properties; the Europa Geophysical Explorer would have been an unlikely focus for astrobiology before the detailed explorations of that moon by the Galileo mission just 7 years ago. This experience assures us that the prime scientific focus of solar system exploration a decade from now, although not necessarily predictable, will certainly be enormously exciting.

CHANGE

The future of solar system exploration will also be conditioned by changes in the infrastructure that guides it, the political system that nurtures it, and the public that supports it. All of these units have considerable inertia against change. However, some changes can be anticipated: for example, the organization and division of responsibility within NASA's Office of Space Science may change. In politics, potential for change in the level of available resources exists following every national election, and it must be remembered that the SSE Survey's list of five prioritized medium-class missions in Chapter 8 is based on the out-year funding levels proposed in the President's budget for 2003, funding levels that are not currently secure. Public support can change in response to dramatic events, as we have recently seen in the possible discovery of the fossilized remains of extraterrestrial life within a meteorite, or possibly, in the future, owing to the unexpected collision of some modestly sized object (100 m or more in size) with the Earth. All of these complexities can affect the future in unknowable ways. All that we can be sure of is that such changes will occur.

Given these uncertainties, is there anything that we can depend upon to help us understand the future of this endeavor? The broad surveys of the subject in Part One give part of the answer: The future program requires a mix between medium- to large-class missions that can adequately challenge current scientific paradigms. It also requires small missions, whether Discovery, Mars Scout, or mission extensions, that can provide focused ways of responding quickly to discoveries made or provide vehicles for entrepreneurial creativity and new scientific ideas. The SSE Survey's proposed Kuiper Belt-Pluto Explorer may be the last great reconnaissance mission within solar system exploration and, if Part One tells a story at all, it is that we are rapidly entering a phase of large- and medium-class missions operating on the surfaces of planets or within their atmospheres and plasma environments that will utilize technologies, yet to be practically developed, that will enable long sojourns, power advanced instrumentation, and return samples to Earth. These technical developments and in situ explorations are essential if we are to achieve acceptable answers to the basic challenges and motivational questions discussed in Part Two.

Solar system exploration is a grand human endeavor. It seeks to discover the nature and origins of the system of planets in which we live, to discover whether life exists beyond Earth, to prepare for human utilization of places in the solar system, and to understand the potential dangers of our space environment. Solar system exploration is also an international endeavor of global extent. That its future is secure seems obvious, even though the details are seen but through a mist. We are compelled to pursue it not only because it represents a physical and technological challenge but also because it places answers to profound questions within our grasp.

Appendixes

Appendix A

Statement of Task

The Space Studies Board will conduct a study to develop a science strategy for solar system exploration. The study will survey the state of knowledge and then lay out the most important scientific questions facing planetary science today. Key areas will include small bodies, primitive bodies including the trans-Neptune realm, the major planets, the moons of the outer solar system, and the inner planets. Because of its rich scientific interest and programmatic prominence, the exploration of Mars will receive individual attention.

The science strategy will contain the following key components:

1. A big picture of solar system exploration—what it is, how it fits into other scientific endeavors, and why it is a compelling goal today;
2. A broad survey of the current state of knowledge about our solar system today;
3. An inventory of the top-level scientific questions that should provide the focus for solar system exploration today; and
4. A prioritized list of the most promising avenues for flight investigations and supporting ground-based activities.

In the special case of Mars, the Board will incorporate the findings of its parallel scientific review of Mars science priorities and implications for NASA's Mars exploration program (*Assessment of Mars Science and Mission Priorities*, National Academy Press-prepublication text, 2001). The Mars Exploration program elements addressed in the earlier study should be treated as a single component in the new survey rather than attempting to reprioritize individual nearer-term (<2007) Mars missions against other solar system exploration mission candidates. Mars science, however, should be well integrated with the broader scientific goals.

In presenting these prioritized objectives, it would be most useful to provide prioritized lists of missions that are too large to be undertaken within the Discovery program (i.e., life cycle costs exceeding $300 million) and that could be expected to go into implementation during the next decade. These lists should be broken down into a small number of cost categories (e.g., <$325 million, $325 million to $650 million, and >$650 million). For objectives that could likely be met within or below the Discovery cost-caps, on the other hand, the most valuable guidance would take the form of prioritized science goals. The report should separate the presentation of specific implementation recommendations from the science discussion. Mars missions should be prioritized separately from non-Mars missions.

In conduct of the study, the scientific community will be as broadly canvassed as possible given the time available. The findings of a number of recent Space Studies Board reports on focused topics in solar system exploration will also be incorporated in the study.

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Appendix B

List of Planetary Community White Papers

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The Solar System Exploration (SSE) Survey has been a priority of the planetary community since its inception. In support of this study, the Division for Planetary Sciences of the American Astronomical Society (DPS/AAS), the Planetary Sciences Section of the American Geophysical Union, the Planetary Geology Division of the Geological Society of America, and the Meteoritical Society sponsored a Planetary Community Decadal Web site, created by the DPS/AAS, that included real-time online community forums and facilitated the creation of community decadal panels with self-selected membership that focused on narrow and broad areas of solar system exploration.

More than 380 scientists participated on these community panels. They identified key issues and priorities for the next decade in their areas and generated 24 white papers that were forwarded to the appropriate SSE Survey panels and Steering Group. These papers are available in a single volume, *The Future of Solar System Exploration, 2003-2013*, published by the Astronomical Society of the Pacific Conference Series.[a]

In addition to these efforts, NRC SSE Survey activities were advertised on the community decadal Web site with links to agendas as available. Notification of upcoming SSE Survey activities and requests for input and community decadal updates were regularly sent out in the DPS/AAS e-mail newsletter and forwarded to the other professional societies for distribution to their members (there is substantial overlap in membership among these societies). The energy, financial resources, and time devoted by the planetary community to this process evidence the strong support for such a study and the broad desire among the community to openly discuss and set priorities to guide our future solar system exploration efforts.

TITLES AND AUTHORSHIP OF COMMUNITY WHITE PAPERS

Dust Astronomy: New Venues in Interplanetary and Interstellar Dust Research

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Appendix C

Results of Planetary Community Survey

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A survey was conducted on the Planetary Community Decadal Web site that posed two questions:

- What were the three most important discoveries of the past decade?
- What are the three most important investigations that should be done in the next 10 years?

The kickoff of the survey was during "NASA Night" at the annual conference of the Division for Planetary Sciences of the American Astronomical Society (DPS/AAS), held in New Orleans in late November 2001. A panel consisting of Michael Belton (chair of the Solar System Exploration Survey's Steering Group), the chairs or vice chairs of the SSE Survey's panels, and Colleen Hartman (NASA director of Solar System Exploration) took input from the audience of more than 200 in an open forum. The survey was sent out over the DPS/AAS e-mail exploder and distributed to the other planetary professional societies, directing everyone to the community Web site. Sixty scientists from 37 institutions responded to the survey. While self-selected and not a rigorous sampling of the planetary community, the results do have considerable value as a guide to what interested groups of people think about and expect from the Solar System Exploration program. It was most interesting that the concatenated opinions did not produce results that have not been already extensively discussed. The survey results are as follows:

- *The three most important discoveries of the past decade:*
  1. Extrasolar planets;
  2. The Kuiper Belt; and
  3. *Tied:* Oceans beneath the surfaces of Europa, Ganymede, and Callisto; and Mars-related discoveries.
- *The three most important investigations for the next decade:*
  1. The Kuiper Belt-Pluto mission (largest individual recommendation);
  2. Missions to and ground-based studies of asteroids and comets; and
  3. *Tied:* Study of extrasolar planets; and study and search for conditions under which life might exist.

Appendix D

Summary of the Planetary Society's Public Opinion Survey

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In conjunction with the Solar System Exploration Survey, the Planetary Society carried out an independent public opinion survey. Since this survey was not done in a controlled and rigorous fashion, significant bias may be latent in the results. However, these biases have been evaluated. The survey results are expected to have value as a guide to what interested people think about and expect from the Solar System Exploration program.

The survey focused on those in the general public who have a particular interest in planetary exploration. Billed as "your opportunity to tell NASA how you would like to be informed about its missions and about future priorities in planetary exploration," the survey asked the following questions:

- What, in your opinion, should be the ultimate purpose of U.S. space exploration?
- Choose (from a list of 15) 5 of the following missions that you think are most important for space agencies to accomplish in the next decade.

Several other questions were also asked that are not particularly pertinent to the present study. The results (paraphrased) found by the Planetary Society are as follows:

1. What, in your opinion, should be the ultimate purpose of the U.S. planetary exploration program? (The top three choices only are given here.)
   a. Scientific exploration (ranked first by 23 percent, first rank overall);
   b. Determining suitability for human colonization (ranked first by 25 percent, second rank overall); and
   c. Looking for dangers to Earth from space (ranked first by 25 percent, third rank overall).

2. Choose five of the following missions that you think are most important for space agencies to accomplish in the next decade. (The top five choices are given here.)
   a. Mars (91 percent)
   b. Moon (65 percent)
   c. Europa (62 percent)
   d. Pluto/Kuiper Belt (37 percent)
   e. Io (34 percent)

Complete results of this survey, which attracted 54,195 responses, can be obtained from the Planetary Society by visiting its Web site at <http://www.planetary.org/html/survey/survey_results.htm> or by e-mailing bruce.betts@planetary.org with questions or to request further details.

Appendix E

Glossary, Abbreviations, and Acronyms

AAS: American Astronomical Society.
accretion: A process in which a star or planet gathers material to itself by gravitational attraction.
airglow: A quasi-steady radiant emission from the upper atmosphere over middle and low latitude.
albedo: The fraction of incident light reflected by a body.
Alfvén conductance: The conductance of a plasma particularly in the presence of a magnetic field.
Alfvén waves: Hydromagnetic shear waves that move along magnetic-field lines; a major acceleration mechanism of charged particles in plasma physics and astrophysics.
alkane: A member of a series of saturated aliphatic hydrocarbons having the empirical formula C_nH_{2n+2}, where n is a positive integer.
aluminosilicate: A colorless, crystalline combination of silicate and aluminate in the form of rhombic crystals.
amino acid: Any of the organic compounds that contain one or more basic amino groups and one or more acidic carboxyl groups and that are polymerized to form peptides and proteins.
andesite: Finely crystalline volcanic rock composed largely of the minerals plagioclase, feldspar, and pyroxene.
AO: Adaptive optics.
APL: Applied Physics Laboratory (Johns Hopkins University).
apoapse: The point in an orbit most distant from the center of attraction.
aromatic compounds: Those compounds that have physical and chemical properties resembling benzene.
AR-SR: Asteroid Rendezvous-Sample Return (mission).
ASI: Agenzia Spaziale Italiana, the Italian national space agency.
astronomical perturbations: Small deviations in the motion of an object caused by changes in the gravitational field or other forces acting on it.
AU: Astronomical unit—the mean distance from Earth to the Sun.

basalt: A volcanic rock composed largely of plagioclase, feldspar, and dark minerals such as pyroxene and olivine.
biosphere: The life zone of Earth, including the lower part of the atmosphere, the hydrosphere, soil, and the lithosphere to a depth of 2 kilometers.
breccia: Rock composed of broken fragments cemented together.

CAPTEM: Curation and Analysis Planning Team for Extraterrestrial Materials.
carbonaceous chondrite: A chondritic meteorite that contains a relatively large amount of carbon and has a resulting dark color.
Cassini: A very large Saturn orbiter launched by NASA in October 1997. Several months after its arrival at Saturn in July 2004, it will deploy the European Space Agency's Huygens Titan probe. It will also conduct complex, multidisciplinary observations of the planet's atmosphere, rings, magnetosphere, and satellites. Cassini conducted coordinated observations of Jupiter with Galileo in late 2000.
CasX: Cassini Extended mission.
CCSR: Comet Cryogenic Sample Return (mission).
Centaur: A family of small solar system bodies found between the orbits of Jupiter and Neptune, having appearances ranging from asteroidal to cometlike. Their orbital characteristics indicate that they have not resided in their present locations very long, leading to the suggestion that they are recently migrated Kuiper Belt objects.
Chassignite: A meteorite composed chiefly of olivine thought to come from Mars.
CHEX: The National Research Council's Committee on Human Exploration.
chirality: The right- or left-handedness of an asymmetric molecule. Absence of symmetry on reflection.
chondrite: A stony meteorite containing chondrules.
chondrule: A roughly spherical body consisting chiefly of pyroxene or olivine minerals embedded in the matrix of certain stony meteorites.
clathrate: A compound in which one component is enclosed by the structure of another.
clinopyroxene: The general term for any of the pyroxenes that crystallize in the monoclinic system.
CNES: Centre National d'Etudes Spatiales, the French national space agency.
CNSR: Comet Nucleus Sample Return.
COEL: The National Research Council's Committee on the Origins and Evolution of Life.
coma: The spherical envelope of gas and dust surrounding the nucleus of an active comet, created when the ambient heat causes the vaporization of cometary material.
comet: A volatile-rich body that develops a transient atmosphere, or coma, as it approaches the Sun. Most observed comets have highly elliptical orbits, sometimes approaching parabolic.
COMPLEX: The National Research Council's Committee on Planetary and Lunar Exploration.
Contour: The Comet Nucleus Tour mission.
corotation resonance: A periodic enforcement of perturbations at the frequency of the orbital motion.
cosmochemistry: The branch of science concerned with the chemical composition of the universe and its origin.
CSSR: Comet Surface Sample Return (mission).

DAP: Data-analysis program.
diapir: A dome or anticlinal fold in which a mobile plastic core has ruptured the more brittle overlying rock.
differentiation: The process by which the interior of a planetary body separates into layers of different compositions.
diking: The process by which a tabular body of rock cuts across the structure of adjacent rocks.
DPS/AAS: Division for Planetary Sciences of the American Astronomical Society.
DSN: Deep Space Network.
dunite: An ultrabasic rock consisting almost solely of a magnesium-rich olivine with some chromite and picotite.
dynamo: An electromagnetic process in which the movement of conductive material gives rise to a magnetic field.

ecliptic: The plane of Earth's orbit around the Sun.
EGE: Europa Geophysical Explorer (mission).
ELAN: Europa Lander (mission).
electron dissociation: The process by which molecules are broken apart through collisions with electrons.
electron spectrometer: A device that measures the distribution of energy in a flux of electrons.
ELV: Expendable launch vehicle.
emission spectrometer: A device that measures the energy emitted by materials due to their intrinsic heat.

endogenous, endogenic: Relating to a processe of internal origin.
eolian: Pertaining to the action or effect of the wind.
E/PO: Education and public outreach.
ESA: European Space Agency.
EUV: Extreme ultraviolet.
exogenous, exogenic: Relating to a process of external origin.
extremophiles: Microorganisms capable of growing under extreme physiochemical conditions, such as high temperatures, pressures, and acidity.
extrusion: Emission of magma or magmatic materials at the surface of a planet.

Fabry-Perot interferometer: A device having two parallel glass plates, silvered on their inner surfaces so that an incoming electromagnetic wave is multiply reflected between them to cause self-interference and then is transmitted.
fluvial: Pertaining to or produced by the action of a river or stream.
FY: Fiscal year.

Galilean satellites: The four largest moons of Jupiter—Io, Europa, Ganymede, and Callisto—first observed by Galileo in 1610.
Galileo: A large Jupiter orbiter launched by NASA in 1989. Following arrival at Jupiter in 1995, it deployed an atmospheric entry probe and subsequently has conducted complex, multidisciplinary observations of the planet's atmosphere, rings, magnetosphere, and satellites. Galileo conducted coordinated observations with Cassini during the latter's Jupiter flyby in late 2000.
geomorphology: The study of the origin of geologic landforms.
geotechnics: Application of scientific and engineering principles to problems by using knowledge of the properties of crustal materials.
Giotto: The European Space Agency launched this spacecraft in July 1985 on a trajectory that enabled it to perform a fast flyby of the nucleus of Halley's Comet in March 1986. Although severly damaged during the encounter, the spacecraft was later reactivated and performed a close flyby of Comet Grigg-Skjellerup in July 1992.
GO: Ganymede Orbiter (mission).
graben: A block of the crust, generally with a length much greater than its width, that has dropped relative to blocks on either side.
GSMT: Giant Segmented Mirror Telescope.

habitable zone: The notional region around a star within which an Earth-like planet would experience environmental conditions compatible with life as we know it. The solar system's habitable zone stretches, approximately, from the orbit of Venus to the orbit of Mars.
heteropolymer: A polymer that consists of a series of two or more different monomers.
HST: Hubble Space Telescope.
Huygens: The European Space Agency's contribution to NASA's Cassini mission. Huygens will be released from Cassini in late 2004 and will conduct in situ observations of Titan's atmosphere and surface.
hydrosphere: All bodies of water on a planet, as distinguished from the lithosphere and the atmosphere.

IDPs: Interplanetary dust particles—tiny particles that once orbited in the space between the planets, normally collected in the stratosphere by high-flying aircraft.
igneous cumulates: Accumulations of igneous rocks.
impact gardening: The process of mixing surface materials by impact.
IO: Io Orbiter (mission).
IRTF: NASA's Infrared Telescope Facility.
ISAS: Institute of Space and Astronautical Science, Japan's space science agency.

ISO: Infrared Space Observatory.
isotopic fractionation: The process by which the isotopic composition of a substance is changed over time due to physical and chemical processes.
ISS: International Space Station.

Joule heat: The heat generated when an electrical current flows through a medium having electrical resistance.
JPL: Jet Propulsion Laboratory.
JPOP: Jupiter Polar Orbiter with Probes (mission).
JWST: James Webb Space Telescope.

KBO: Kuiper Belt object—a general name for the bodies found in the Kuiper Belt.
KBP: Kuiper Belt-Pluto (Explorer mission).
komatiite: Mantle-derived igneous rock with a content high in magnesium.
Kuiper Belt: A region of the solar system containing icy planetesimals distributed in a roughly circular disk some 40 to 100 AU from the Sun. Pluto is believed to circumscribe the innermost region of the Kuiper Belt.

Langmuir probe: A device for measuring the temperature and electron density of a plasma.
LDEF: Long Duration Exposure Facility.
lherzolites: Peridotite composed principally of olivine.
LIBS: Laser Induced Breakdown Spectroscopy.
Lindblad resonance: A celestrial-mechanics phenomenon occurring when an orbiting object encounters periodic crests of a gravitational potential at the same frequency as its radial oscillations.
lineament: A straight or gently curved, lengthy topographic feature.
lithosphere: The rigid outer crust of rock of a planetary body.
littoral drift: Materials moved by waves and currents of the littoral zone.
LSAPT: Lunar Sample Analysis Planning Team.
LSST: Large Synoptic Survey Telescope.
Luna: A series of some 24 spacecraft launched to the Moon by the former Soviet Union between 1959 and 1976. The series included three successful sample-return missions (Lunas 16, 20, and 24) and the deployment of two Lunokhod rovers (Lunas 17 and 21).

Magellan: A NASA spacecraft launched in May 1989. In the period August 1990 to October 1994, the spacecraft conducted orbital observations of Venus, including the complete radar mapping of the planet's cloud-shrouded surface.
magnetic dipole moment: A property of the magnetic field induced by a current loop.
magnetosphere: The region exterior to a planet in which its magnetic field plays the dominant part in controlling the physical processes that take place there.
MAO: Mars Upper Atmosphere Orbiter (mission).
Mariner: A series of 11 planetary spacecraft launched by NASA in the period from 1962 to 1973. The series included successful flyby missions to Venus (Mariner 2, 5, and 10), Mars (Mariners 4, 6, and 7) and Mercury (Mariner 10), and the first Mars orbiter (Mariner 9).
MEP: Mars Exploration Program.
MEPAG: NASA's Mars Exploration Payload Assessment Group.
MeSR: Mercury Sample-Return (mission).
MGS: Mars Global Surveyor.
microwave radiometer: A receiver for detecting microwave thermal radiation.
ML^{3}N: Mars Long-Lived Lander Network (mission).
MOLA: Mars Orbiter Laser Altimeter.
morphology: The field that deals with the structure and form of an object at any stage in its evolution.
MQF: Mars Quarantine Facility.

MRO: Mars Reconnaissance Orbiter.
MSL: Mars Science Laboratory (mission).
MSR: Mars Sample Return (mission).
mucilage: An organic material that has gluelike properties.
MUSES-C: A Japanese science and technology-development mission designed to rendezvous with an asteroid, collect samples of its surface material, and return them to Earth for study.
MWG: Meteorite Working Group.

nakhlite: A meteorite composed of an aggregate of diopside and olivine thought to come from Mars.
NAS: National Academy of Sciences.
NASA: National Aeronautics and Space Administration.
NASDA: National Space Development Agency of Japan.
NEAR: Near-Earth Asteroid Rendezvous (mission).
NEO: Near-Earth object.
NEP: Nuclear-electric propulsion—a reaction drive that utilizes a fission reactor to power an ion engine.
neutral mass spectrometer: A device that measures the distribution of atomic and molecular masses in a beam of neutral particles.
NGLT: Next Generation Lowell Telescope.
Noachian era: The earliest recognizable epoch in martian geologic history. It is characterized by a heavy cratering rate and the earliest preserved rocks.
NOP: Neptune Orbiter with Probes (mission).
NOTE: Neptune Orbiter/Triton Explorer (mission).
NRC: National Research Council.
NSF: National Science Foundation.
NVO: National Virtual Observatory.

obliquity: The angle between the orbital plane of an object and the plane of its rotational equator.
occultation: The disappearance of the light of a celestial body owing to the intervention of another body of larger apparent size across the line of sight.
OES: NASA's Office of Earth Science.
OM: Organic matter.
OMB: Office of Management and Budget—part of the Executive Office of the President.
Oort cloud: A spherical distribution of comets having semimajor axes between 1,000 and 50,000 AU, typically with low orbital eccentricity.
orthopyroxene: A series of pyroxene minerals crystallizing in the orthorhombic system.
OSF: NASA's Office of Space Flight.
OSS: NASA's Office of Space Science.
outgassing: The emanation of gases from within an object.

PDS: Planetary Data System.
periapse: The point in a orbit closest to the center of attraction.
perihelion: The point at which a body's orbital motion takes it closest to the Sun.
photochemistry: The study of the effects of light on chemical reactions.
photometry: Measurement of light intensities.
phylogenetic: Pertaining to the relationship between different organisms. Such relationships are typically based on comparisons between the genetic characteristics of different organisms.
PI: Principal investigator.
Pioneer: A series of 13 NASA spacecraft launched between 1958 and 1978. The series included the first missions to Jupiter (Pioneer 10 and 11) and Saturn (Pioneer 11) and culminated with two missions to Venus (Pioneer Venus 1 and 2).

planetesimals: The planetary bodies that formed the building blocks of all the solar system's planets and satellites.
plasma wave: A disturbance of a plasma involving oscillation of its constituent particles and of an electromagnetic field, which propagates from one point in the plasma to another without net motion of the plasma.
pyroxene: A ferromagnesium rock-forming mineral having infinite (Si_20_6) single inosilicate chains as its principal motif.

R&A: Research and analysis.
racemic mixture: A mixture with equal quantities of crystals of pure dextrorotatory and levorotatory isomers, making it optically inactive.
radiogenic: Relating to the decay of radioactive isotopes.
radioisotope: A radioactive isotope.
radiometric age: The age of an object as determined by measurement of its radioactive isotopes and their stable end-products.
reflectance spectroscopy: Measurement of the spectral radiant flux reflected from a surface.
regolith: The layer of fragmented, incoherent rocky debris on the surface of a planetary body.
retarding potential: An electric potential that causes the speed of a charged particle to be reduced.
Roche zone: The region about a planet where tidal forces are sufficiently strong to tear apart an idealized fluid body.
Rosetta: A large European Space Agency mission originally scheduled for launch in 2003 and designed to rendezvous with and conduct extended studies of comet 46 P/Wirtanen in 2011. Problems with its launch vehicle have delayed the launch until 2004 at the earliest. Its target comet is currently under review.
RPS: Radioisotope power system.
RTG: Radioisotope thermoelectric generator.

SBN: Small Bodies Node (of the Planetary Data System).
scarp: A cliff or steep slope of some extent, generally separating two level or gently sloping areas.
SDT: Science definition team.
shergottite: A type of meteorite with a basaltic composition consisting chiefly of pigeonite and maskelynite that is thought to come from Mars.
SIM: Space Interferometry Mission.
sinter: To coalesce into a single mass by application of pressure or heat, but without melting.
SIRTF: Space Infrared Telescope Facility.
SKA: Square-Kilometer Array.
SNC: A group of meteorite types thought to have originated on Mars.
SOFIA: Stratospheric Observatory for Infrared Astronomy.
solar-electric propulsion: Reaction system that utilizes solar energy to power an ion engine.
solar nebula: The cloud of gas and dust from which our Sun, the planets, and other bodies in the solar system formed.
space weathering: Alteration of an atmosphereless planetary body's (e.g., an asteroid's) surface materials by exposure to the space environment.
SPA-SR: South Pole-Aitken Basin Sample-Return mission.
SR&T: Supporting Research and Technology.
SSB: The National Research Council's Space Studies Board.
SSE Survey: Solar System Exploration Survey.
stochastic: Random.
stratigraphy: The study of the relationships between stratified rocks.
stratosphere: The region above the troposphere, where a planet's atmosphere becomes stably stratified as a result of solar heating.
stromatolite: A multilayered structure in calcareous rocks that are believed to be of algal origin.
STScI: Space Telescope Science Institute.

supercritical fluid: A fluid at a temperature and pressure above its critical point exhibiting the characteristics of both a liquid and a gas.
SWAS: Submillimeter Wave Astronomy Satellite.

TEX: Titan Explorer (mission).
TGN: Terrestrial Planet Geophysical Network (mission).
thermosphere: The uppermost region of a planet's atmosphere, where the temperature increases with height as a result of strong heating from above and where molecular diffusion of heat plays a major role in vertical heat transport.
tholin: The reddish, tarlike organic residue created in simulations of the action of ultraviolet radiation on gases typically found in planetary environments.
tidal heating: The internal heating of a planetary body owing to friction caused by the differential gravitational effect of an external body on the mass in question.
TPF: Terrestrial Planet Finder (mission).
TRF: Trojan/Centaur Reconnaissance Flyby (mission).
Trojan: A clustering of asteroids that is found at the gravitational-equilibrium points 60 degrees ahead of and behind Jupiter in its orbit about the Sun.
tropopause: The boundary between the troposphere and stratosphere, often characterized by an abrupt change in the rate at which the temperature varies as a function of height.
troposphere: The lowermost portion of a planet's atmosphere, in which temperature decreases with height and thermal convection takes place.
T Tauri: A type of irregular variable star whose spectrum shows broad and very intense emission lines; these are believed to be young stars that have not yet reached the main sequence. The Sun is believed to have exhibited T Tauri characteristics early in its history.
T Tauri phase: An early phase in the evolution solar-type stars characterized by extreme variability and mass loss.

ultramafic: Igneous rock composed principally of mafic (magnesium and iron) minerals, such as olivine and pyroxene.
ultraviolet spectrometer: A device that produces a spectrum of ultraviolet light.
UOP: Uranus Orbiter with Probe (mission).

Venera: A very successful series of some 16 flyby, orbiter, and lander missions to Venus launched by the former Soviet Union in the 1961-1983 period.
Viking: A pair of orbiters and landers launched by NASA to explore Mars in August and September 1975. Viking 1 and 2 orbiters functioned in orbit about Mars until July 1978 and August 1980, respectively. The Viking 1 and 2 landers operated on the martian surface from July and September 1976 until November 1982 and April 1980, respectively.
VISE: Venus In Situ Explorer (mission).
vitric: Referring to a pyroclastic material that is characteristically glassy (contains more than 75 percent glass).
volatile: Elements that condense from or exist as a gas at low temperatures.
Voyager: A pair of deep-space missions launched by NASA to the outer solar system in 1977. Between them, these spacecraft conducted close-up observations of Jupiter (1979), Saturn (1980 and 1981), Uranus (1986), and Neptune (1989).
VSR: Venus Sample-Return (mission).

Z-axis accelerometer: A device that measures the rate of acceleration along a particular direction.
zodiacal cloud: A lenticular-shaped dust cloud surrounding the Sun and maintained by fine material from asteroidal collisions and cometary activity.

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